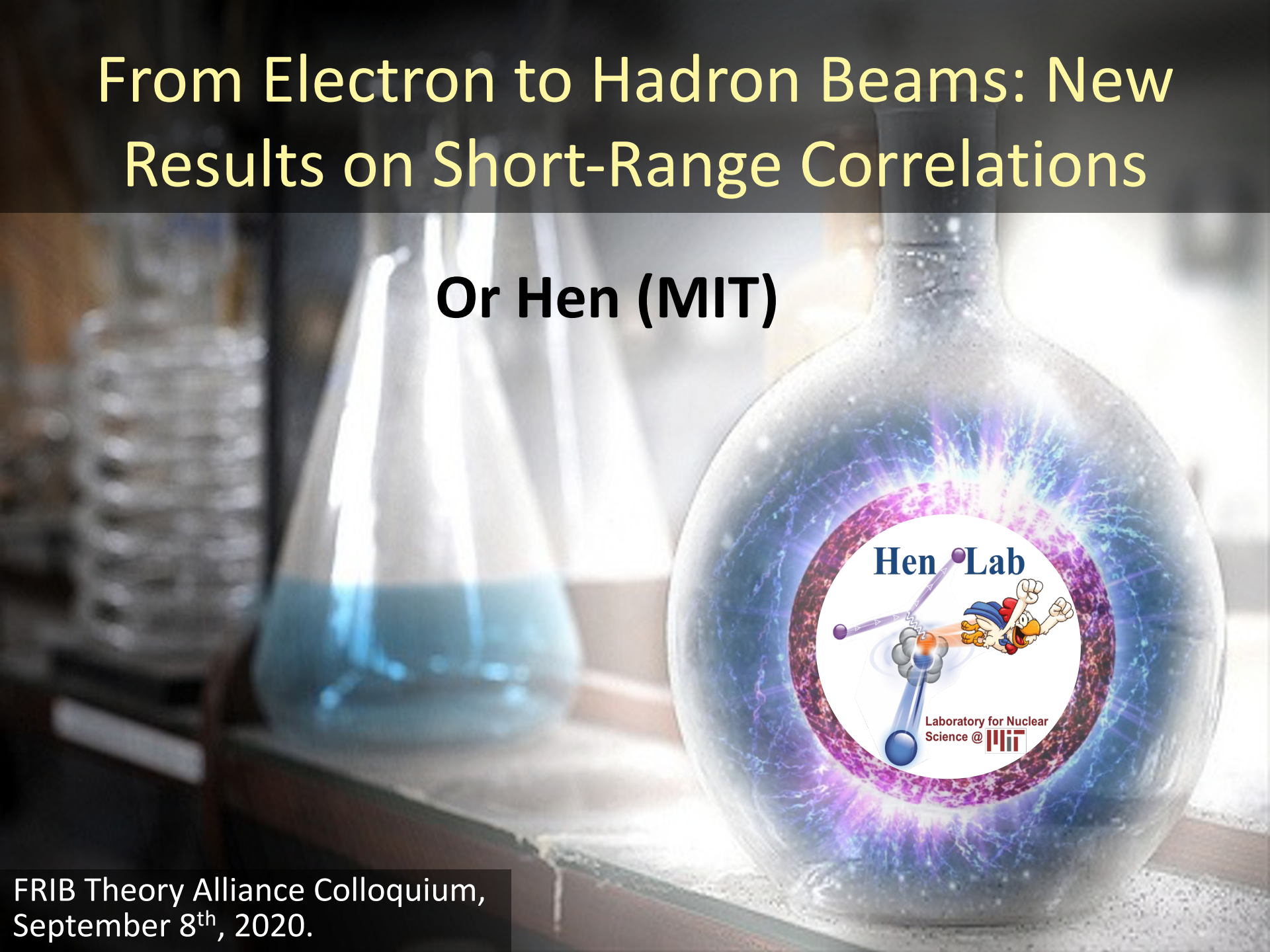
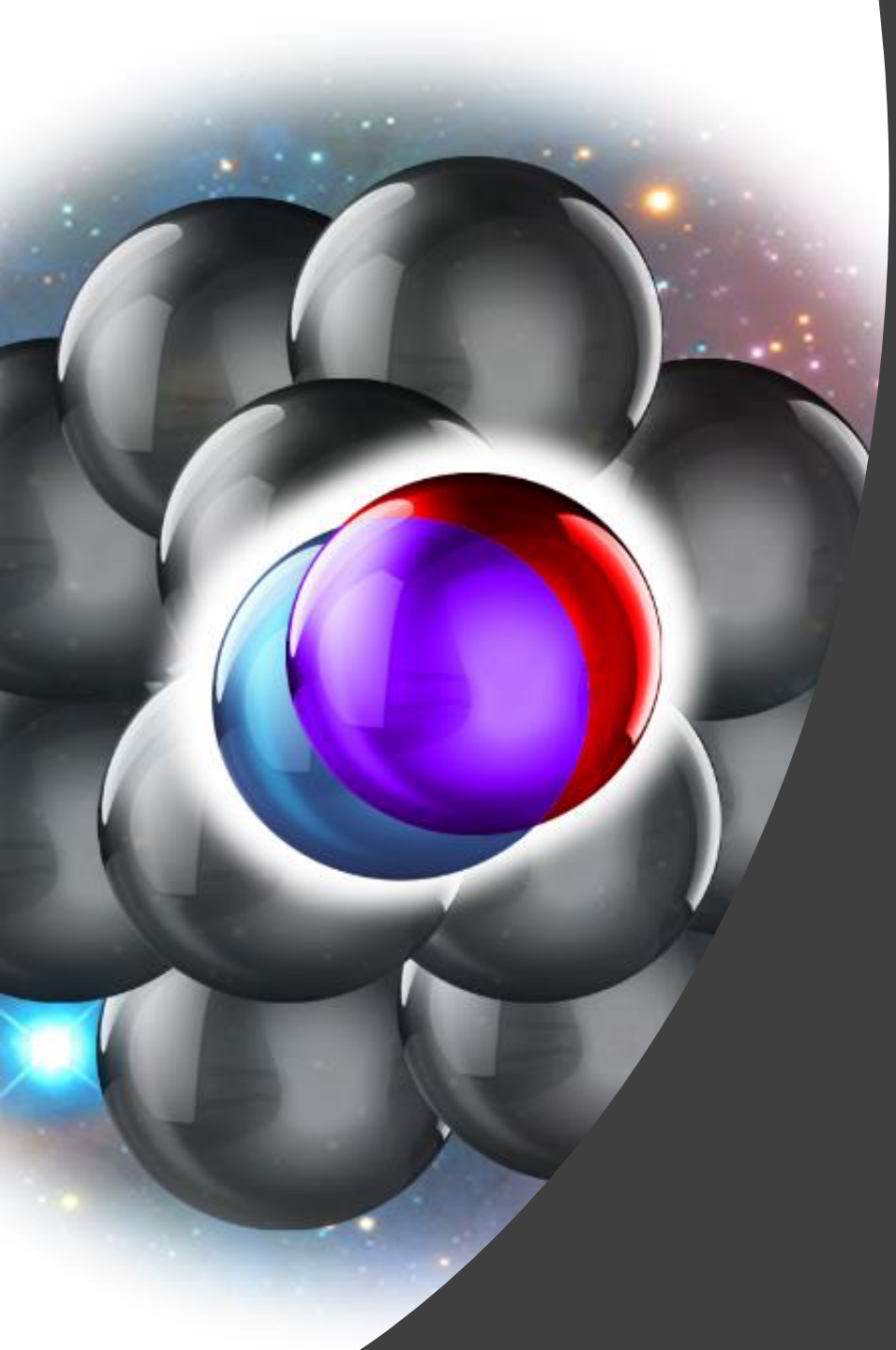
From Electron to Hadron Beams: New Results on Short-Range Correlations

Or Hen (MIT)

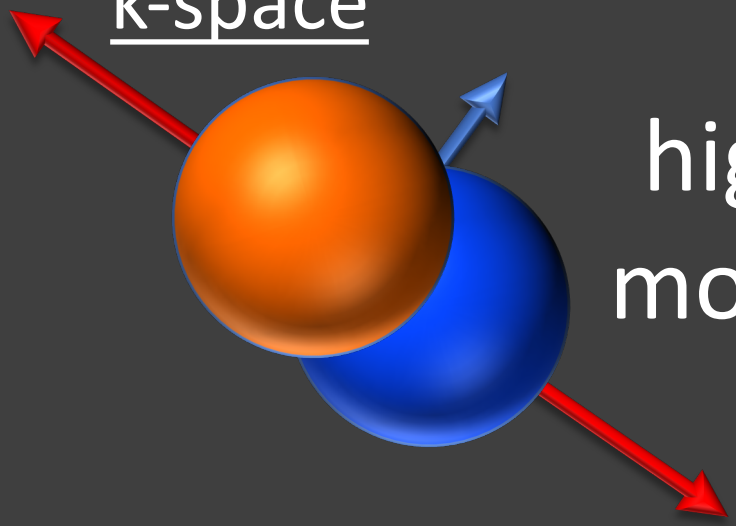


FRIB Theory Alliance Colloquium,
September 8th, 2020.



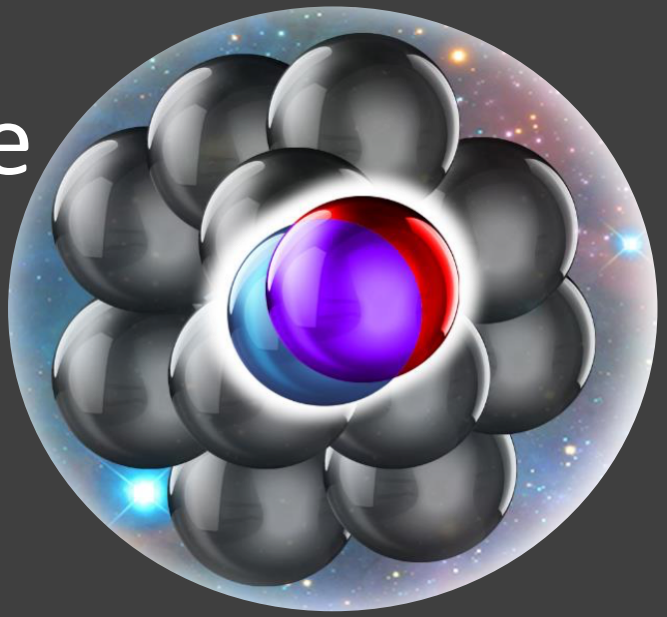
Short-Range Correlations (SRC)

k-space



high ***relative*** and low ***c.m.*** momentum compared to k_F

r-space

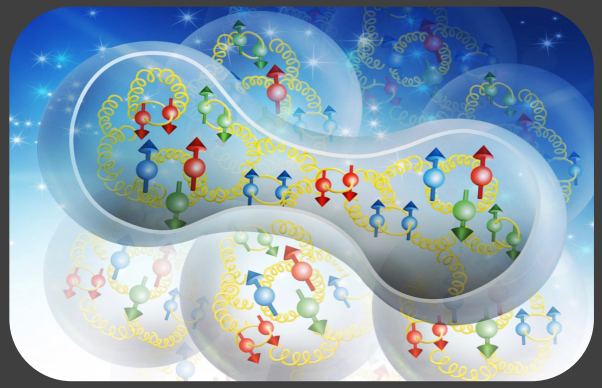


Nucleon pairs that are close together in the nucleus

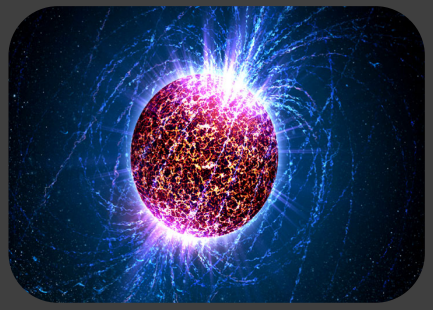
Why SRC?

Required for a high-resolution, first principle, description of nuclear systems & processes.

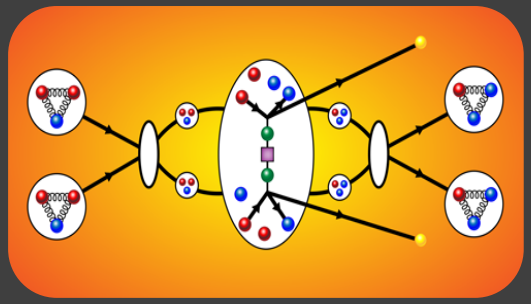
NN interaction from QCD & QCD in nuclei



High-density systems



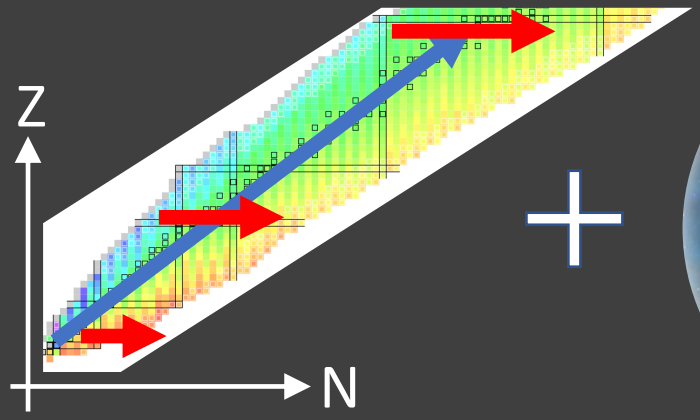
High-q processes
(e.g. $0\nu\beta\beta$ decay)



Today: Overview of present And discussion of future

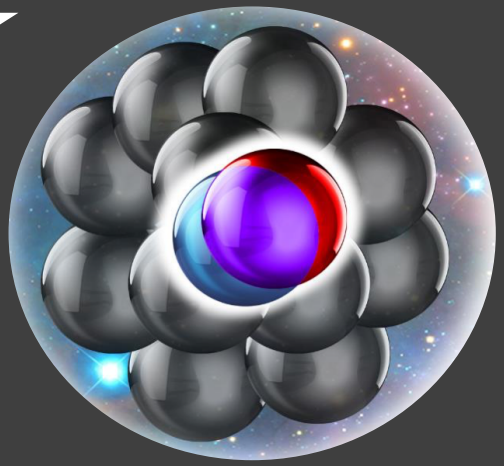
Discussion of future

Radioactive-Ion Beam Physics



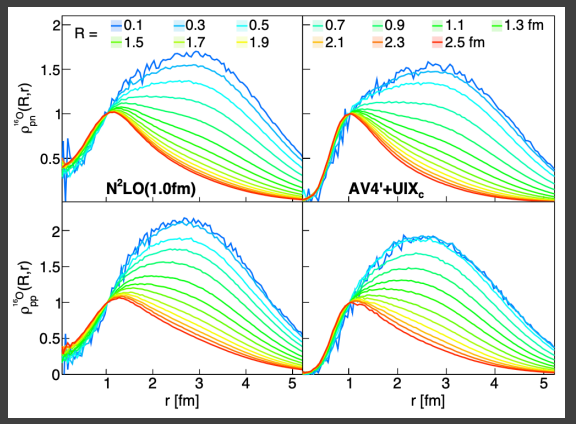
+

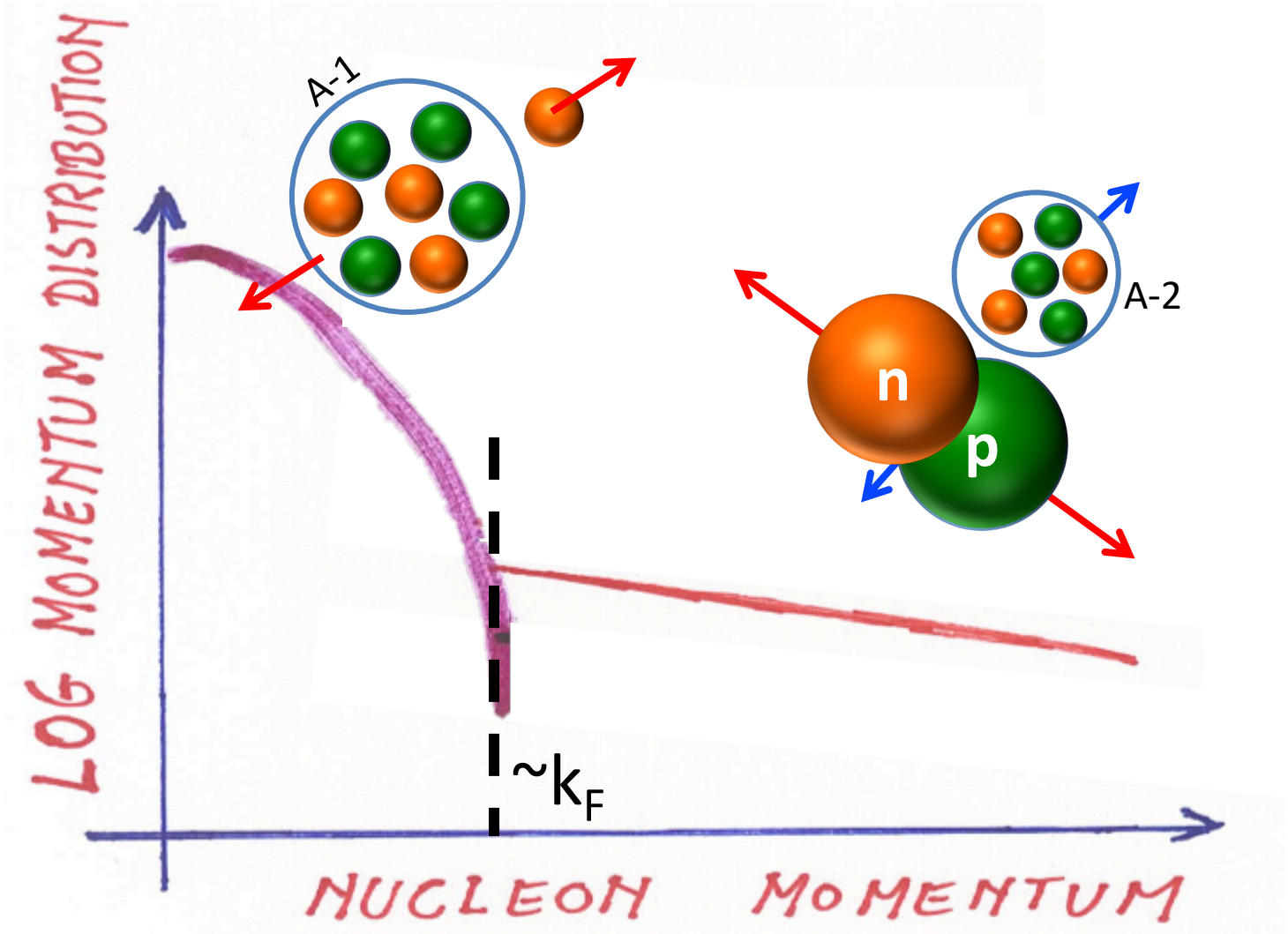
Short-Range Correlations



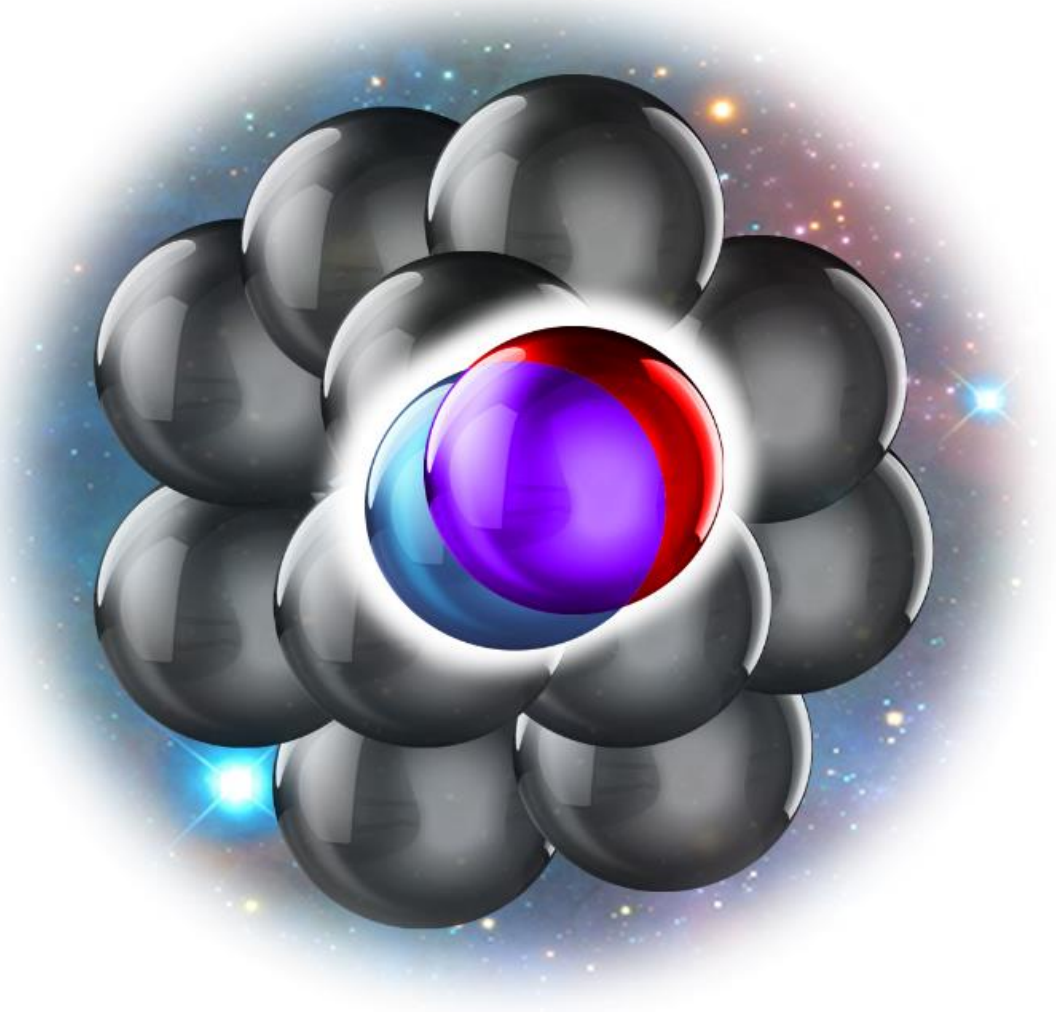
+

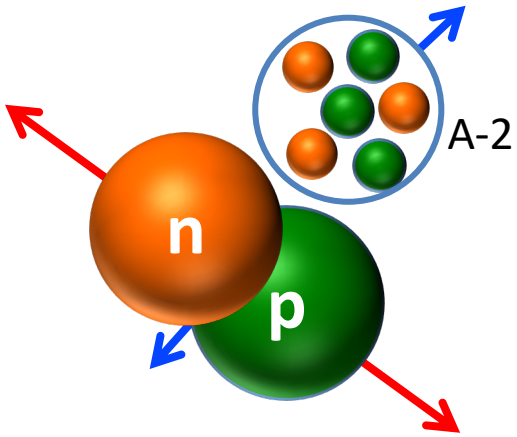
Effective scale separation formalism



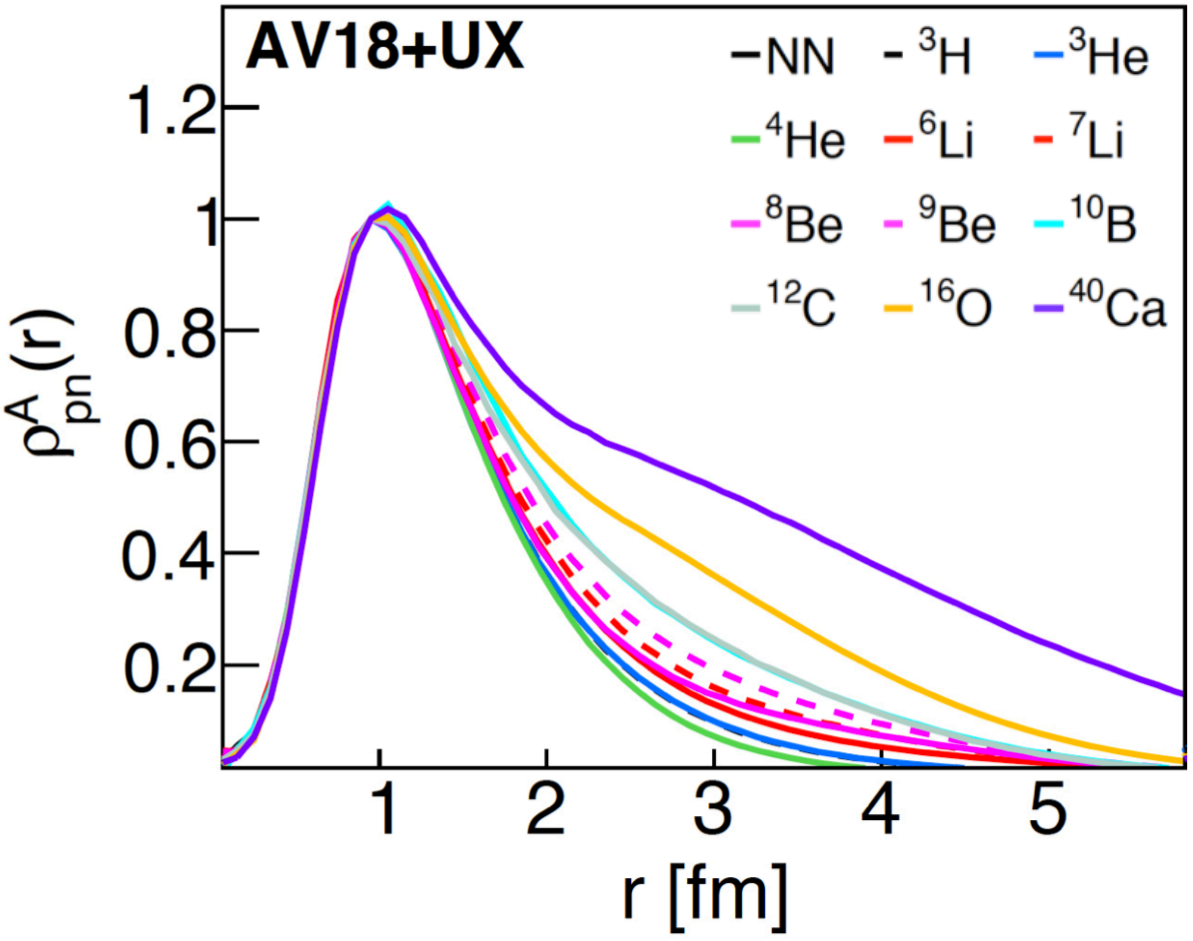

LOG MOMENTUM DISTRIBUTION
A-1
A-2
n
p
~k_F
NUCLEON MOMENTUM

Pairs ⇔ Scale Separation



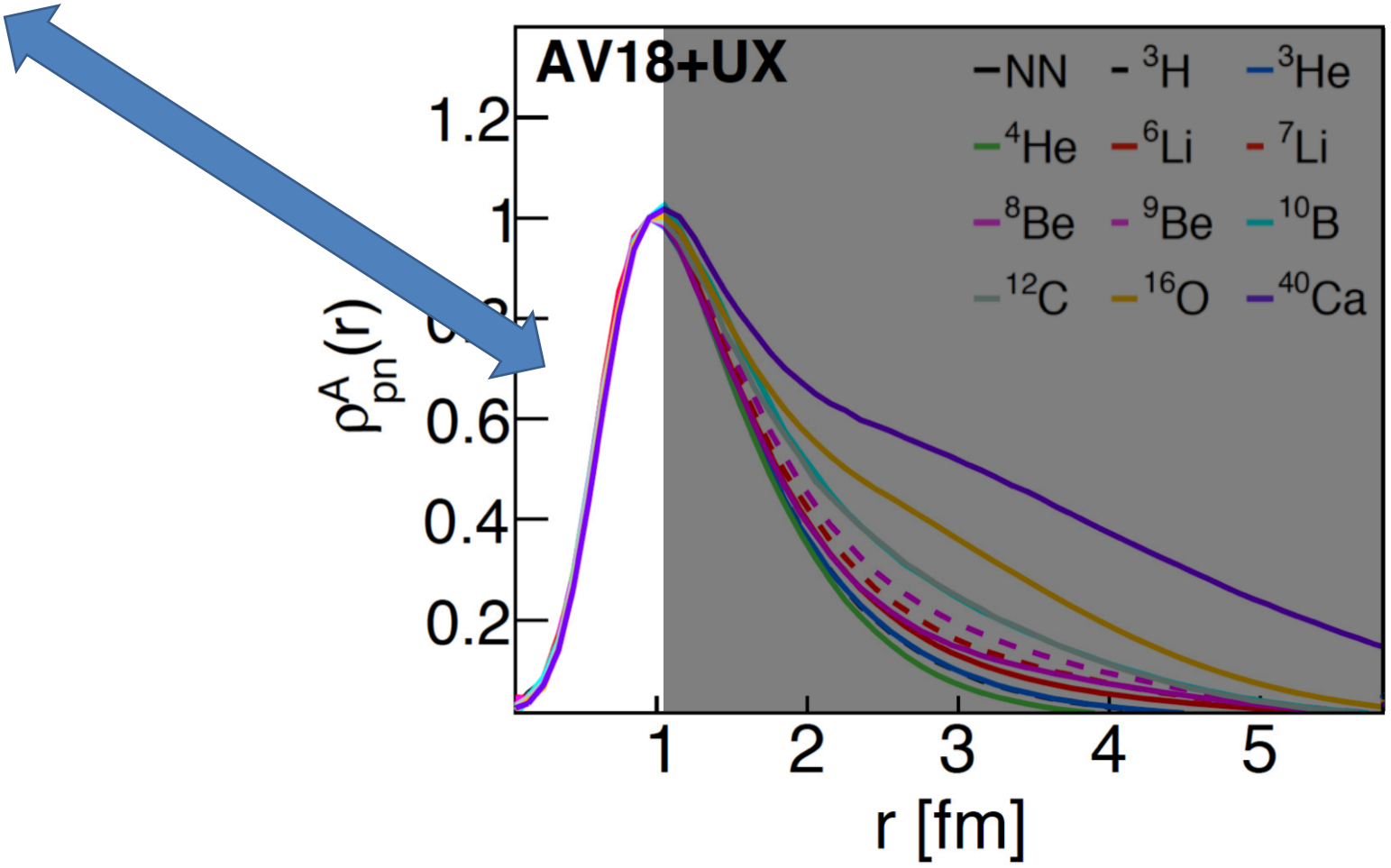


Pair Distance Distributions



Cruz Torres et al., Nature Physics (2020)

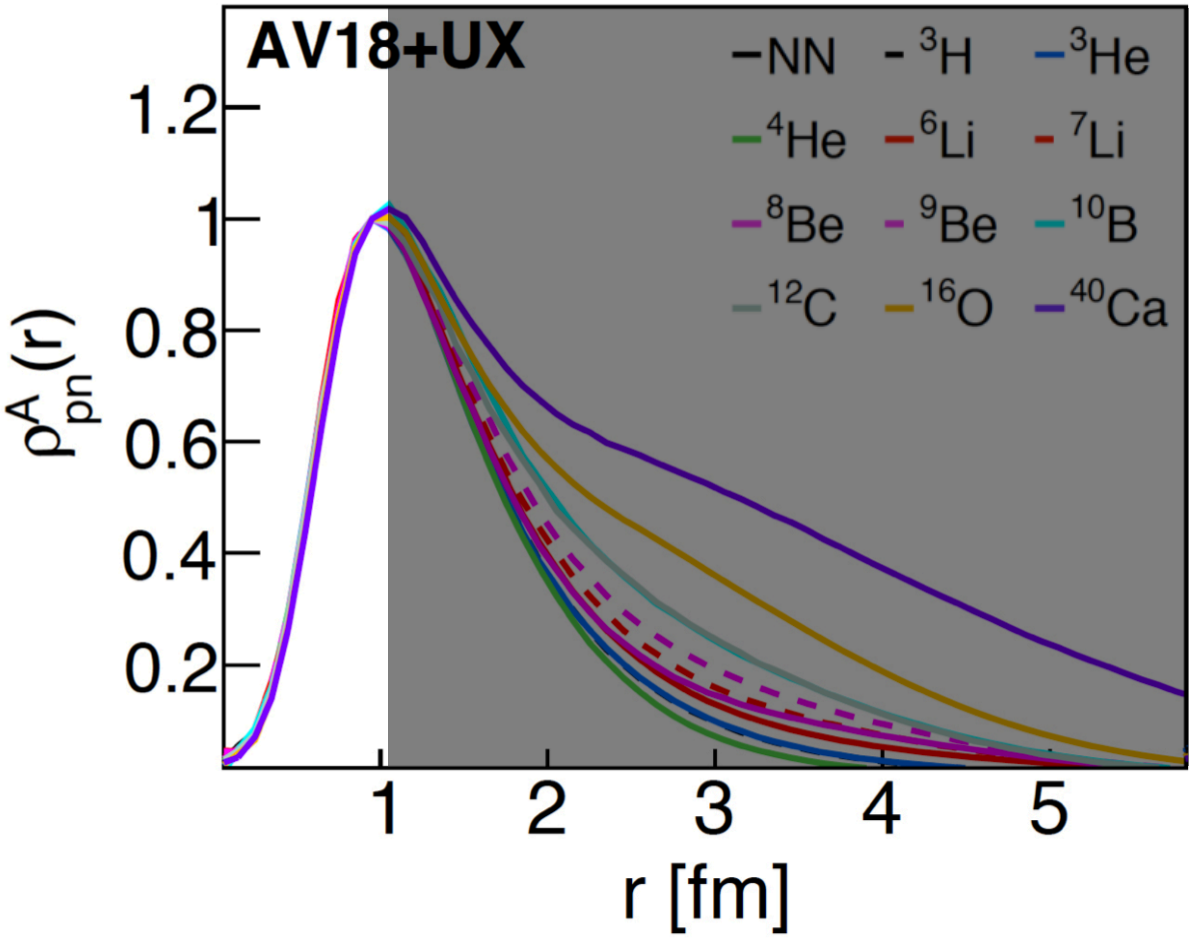
Many Body = Constant x Two-Body



Cruz Torres et al., Nature Physics (2020)

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

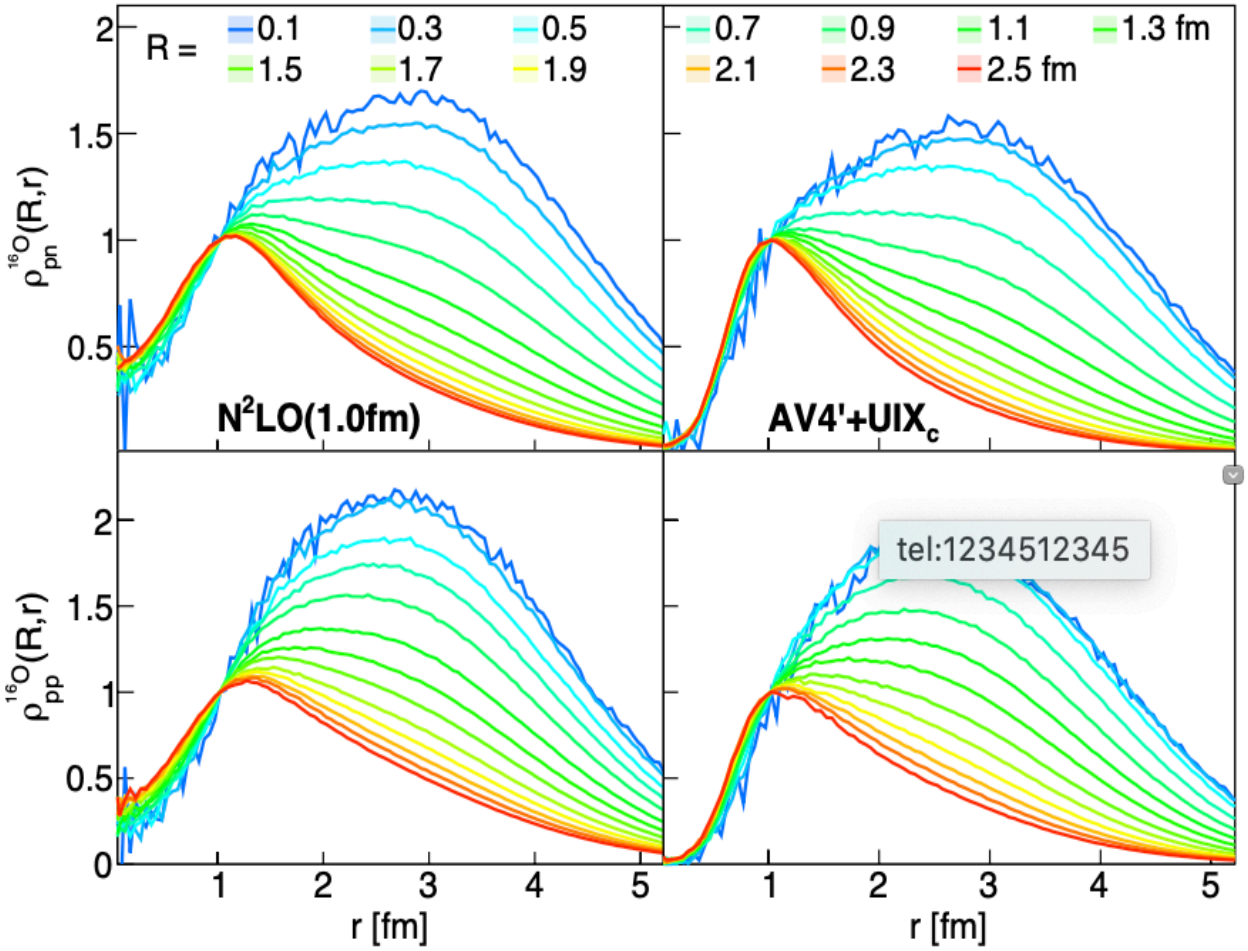
Many Body = Constant x Two-Body



Cruz Torres et al., Nature Physics (2020)

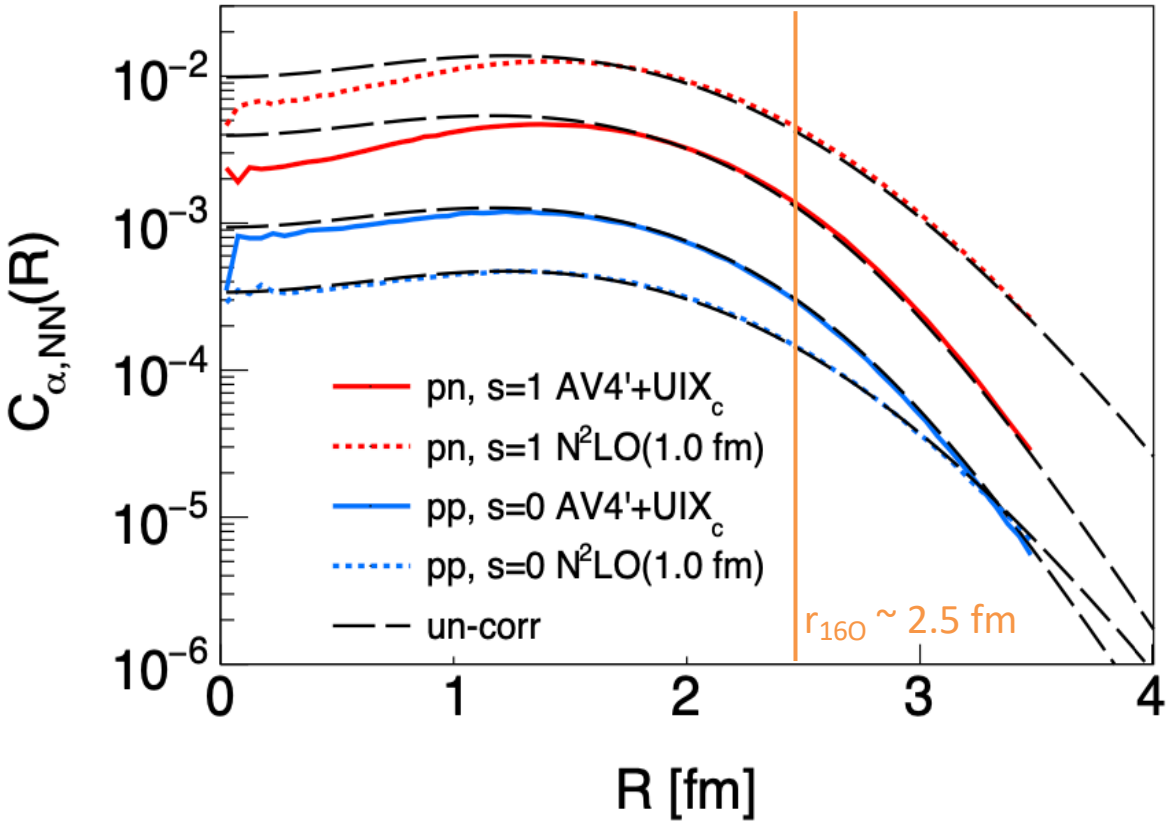
Factorization is *Position* Independent

^{16}O



Cruz Torres et al., Nature Physics (2020)

SRC Pairs Density



$$C^A_{NN}(R) = \int_0^{1\,fm} d\Omega_R d\boldsymbol{r}\ \ \rho^A_{NN}(r,R) \,/\, |\varphi_{NN}(r)|^2$$

Cruz Torres et al., Nature Physics (2020)

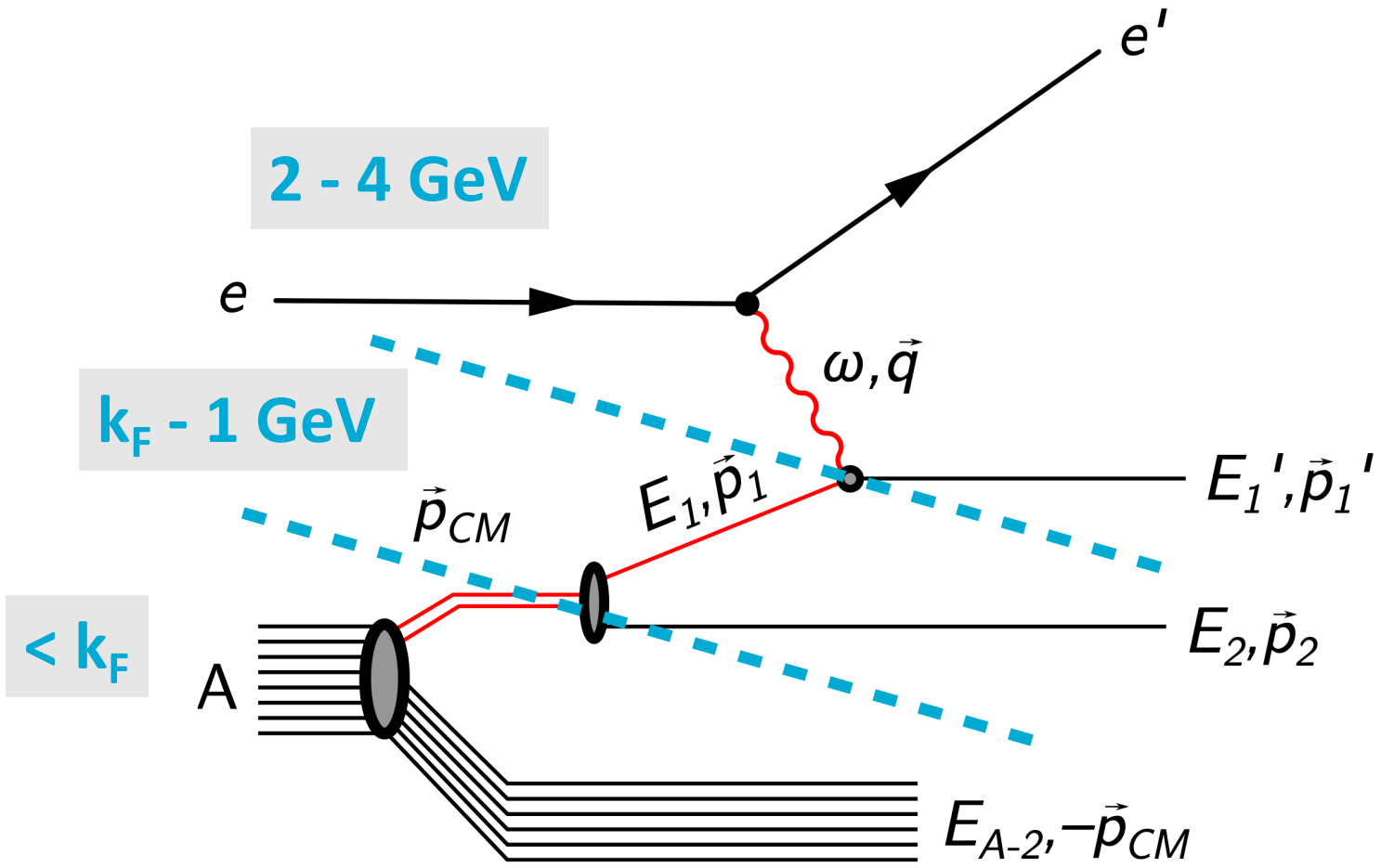
Scale Separation

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Total Dist. = Constant (Low-Energy) x Two-body (High-Energy)

R. Cruz-Torres et al., Nature Physics (2020)
R. Weiss et al., Phys. Lett. B 780 (2018)
J.-W. Chen, W. Detmold, J. E. Lynn, A. Schwenk, PRL 119 (2017)
R. Weiss, B. Bazak, N. Barnea, Phys. Rev. C 92 (2015)

Scale Separation and re-interactions



Lots to discuss about theory…

…but this in an experimental talk!

1. JLab
   - (e,e’NN): NN interaction
   - (e,e’): Pair abundances

2. JINR
   - (p,2p A-2)n: fully exclusive SRCs

3. Neutron Rich Systems
   - Insight from (e,e’N)
   - Interpretability of (e,e’)

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   - Insight from (e,e’N)
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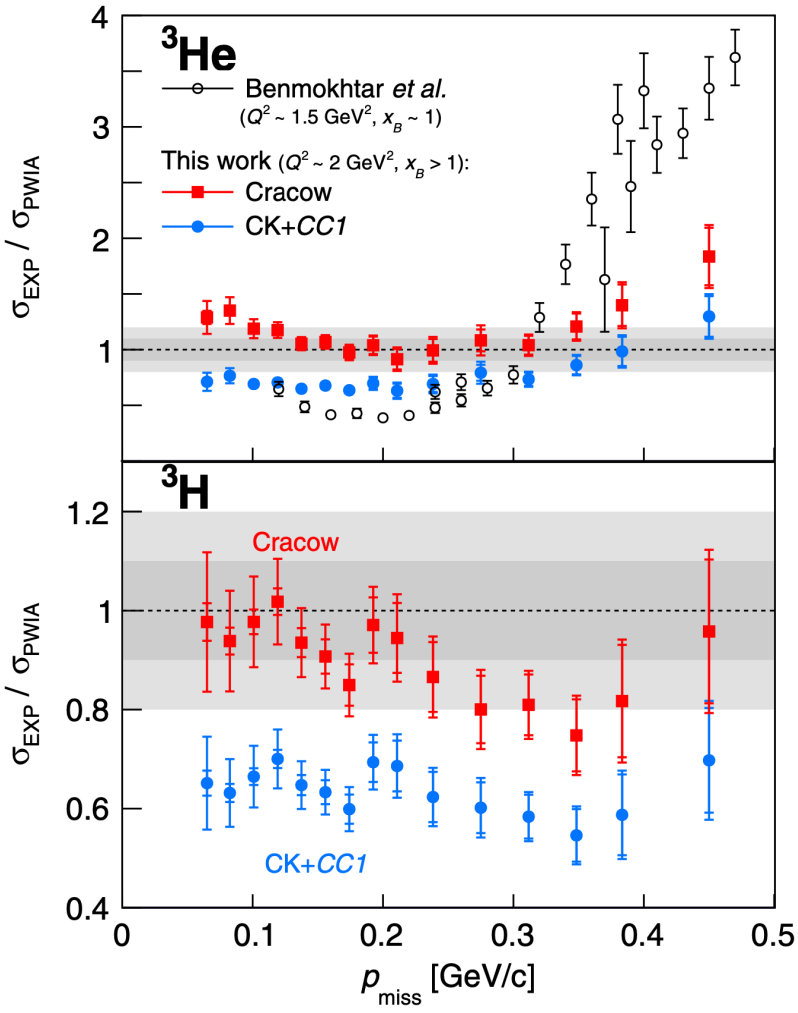
High-Q^2 Studies of A = 2 & 3

Great success for theory!

[Cracow group]

^{3}H works better than ^{3}He.




Cruz Torres and Nguyen et al., PRL (2020)

High-Q^2 Studies of A = 2 & 3

Great success for theory!

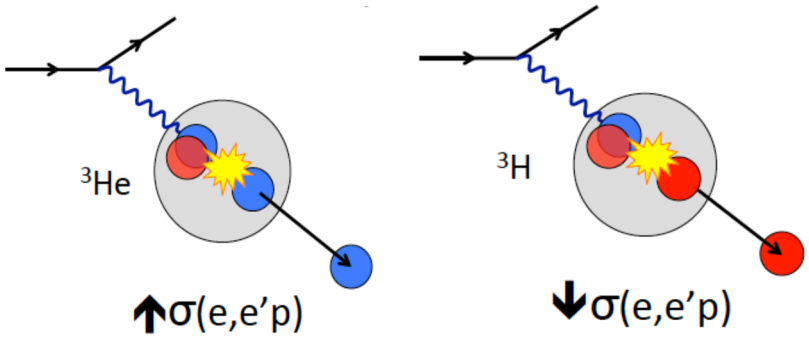
[Cracow group]

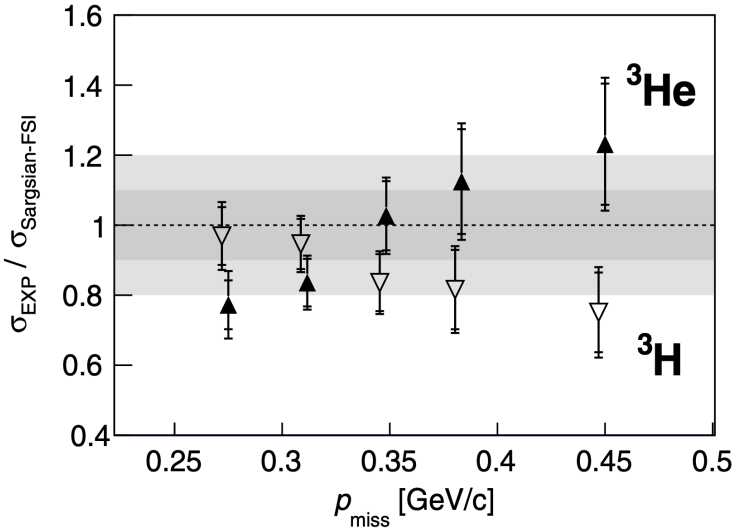
^{3}H works better than ^{3}He.

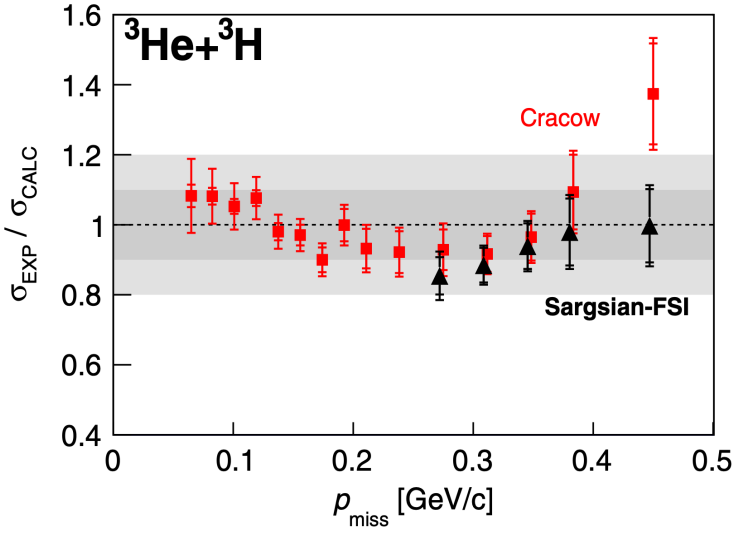
Glauber improves theory.

[M. Sargsian]

<u>SCX can explain the trends</u>



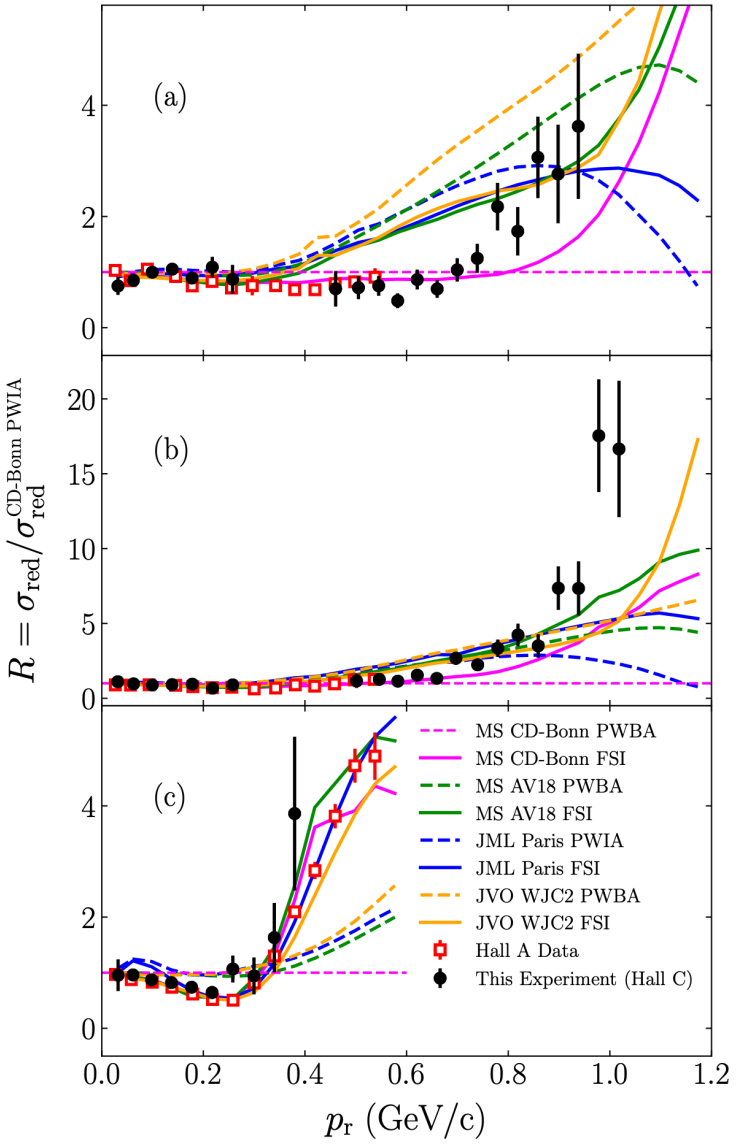




Cruz Torres and Nguyen et al., PRL (2020)

High-Q^2 Studies of A = 2 & 3

Deuteron data can also help understand the high-resolution picture…

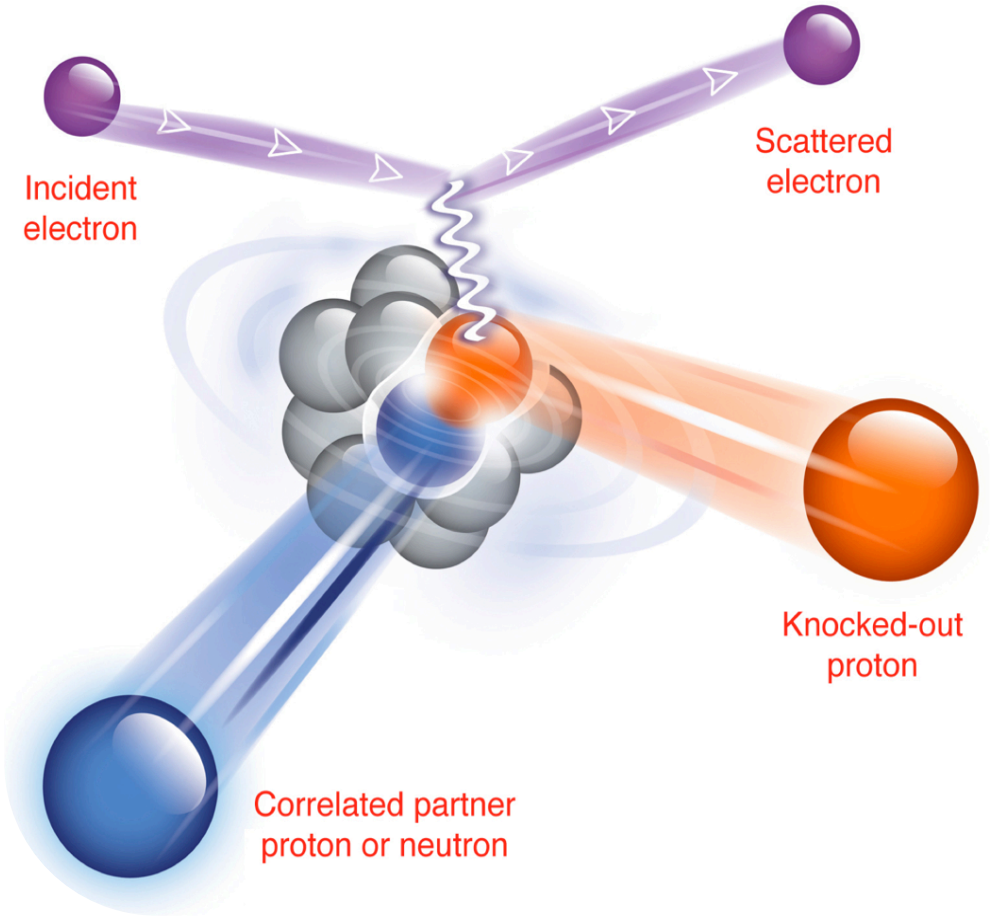


Yero et al., arXiv: 2008.08058 (2020)

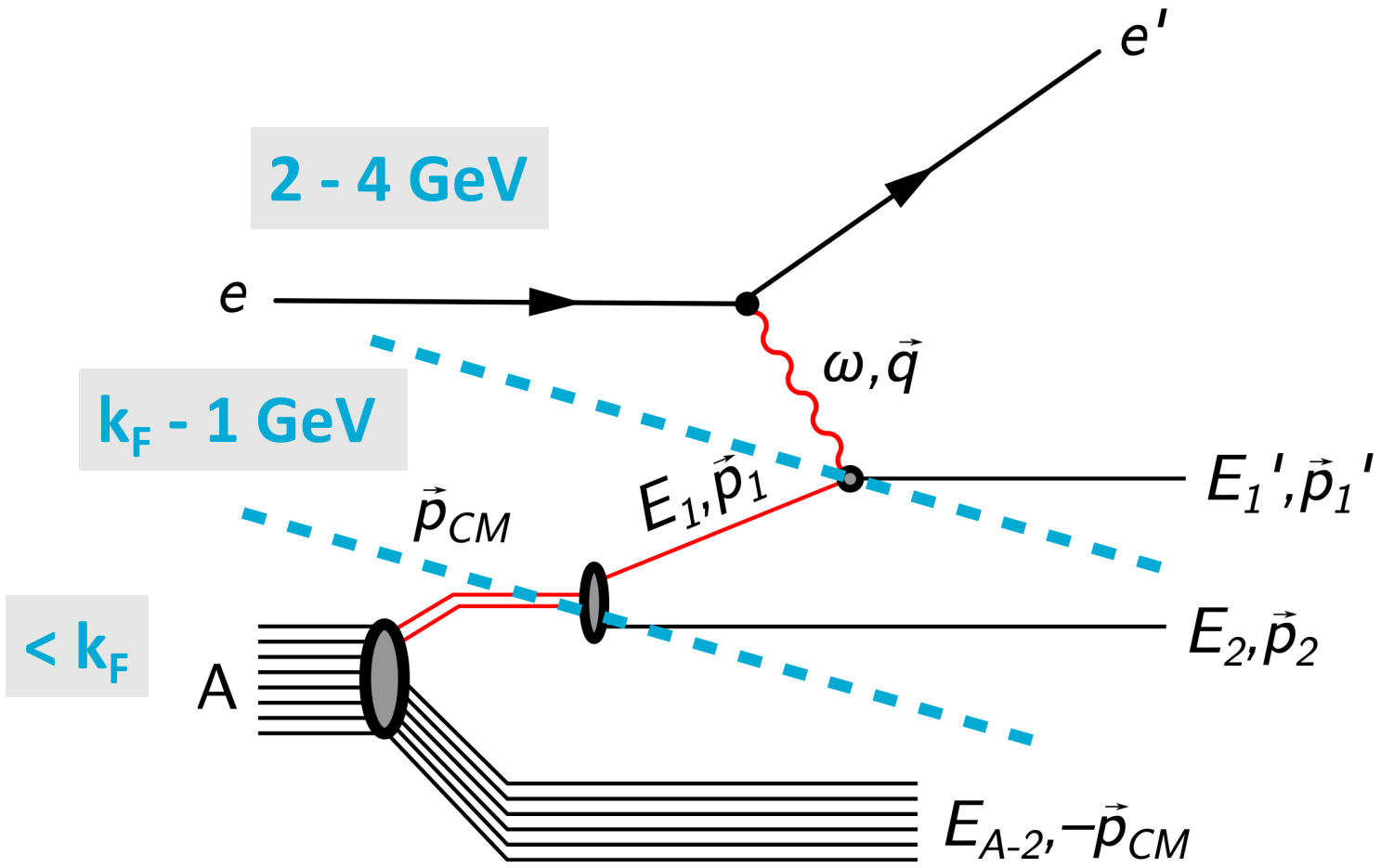
Breakup the pair =>

Detect ***both*** nucleons =>

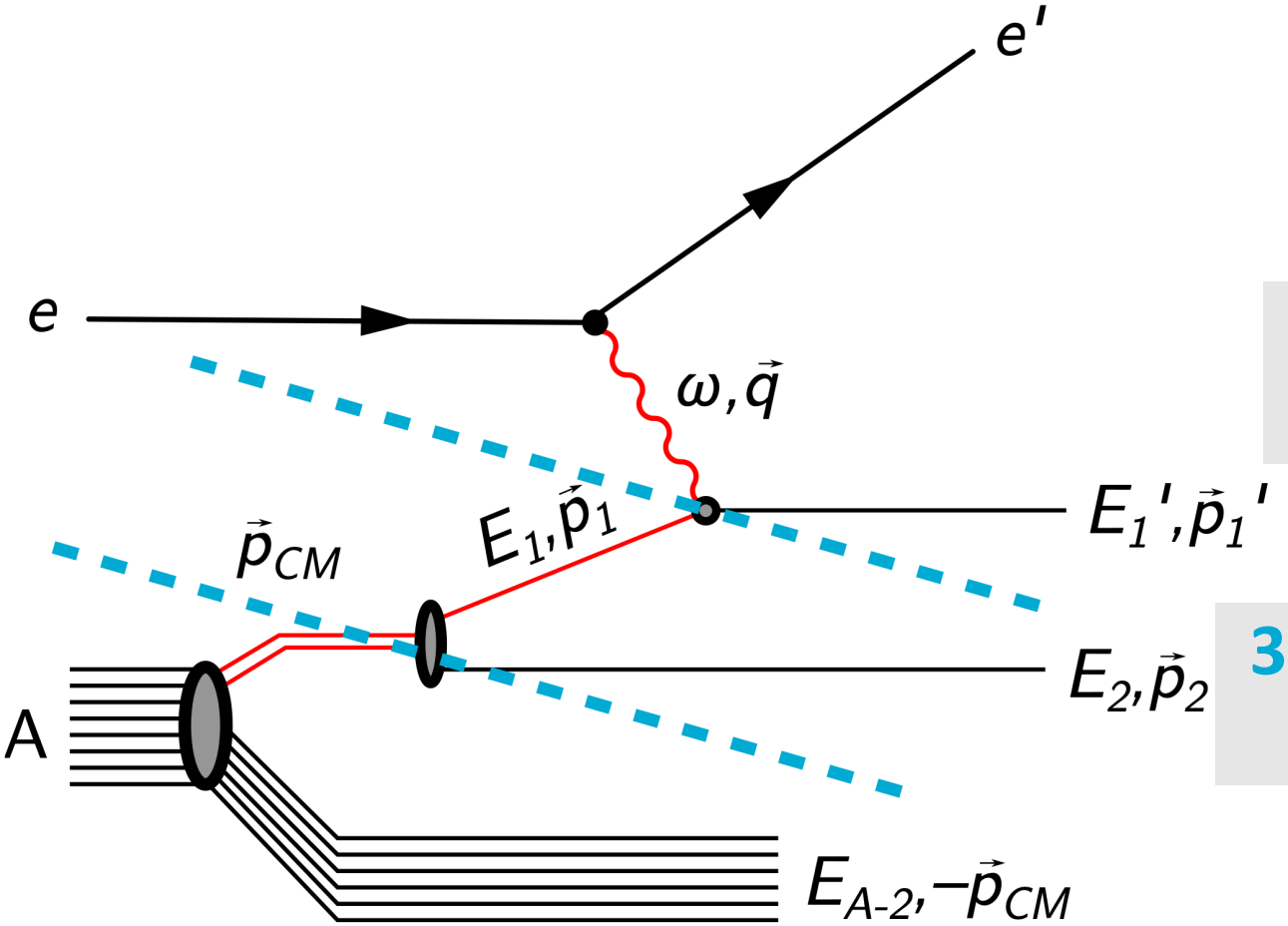
Reconstruct ‘initial’ state



Scale Separation and re-interactions



Scale Separation and re-interactions

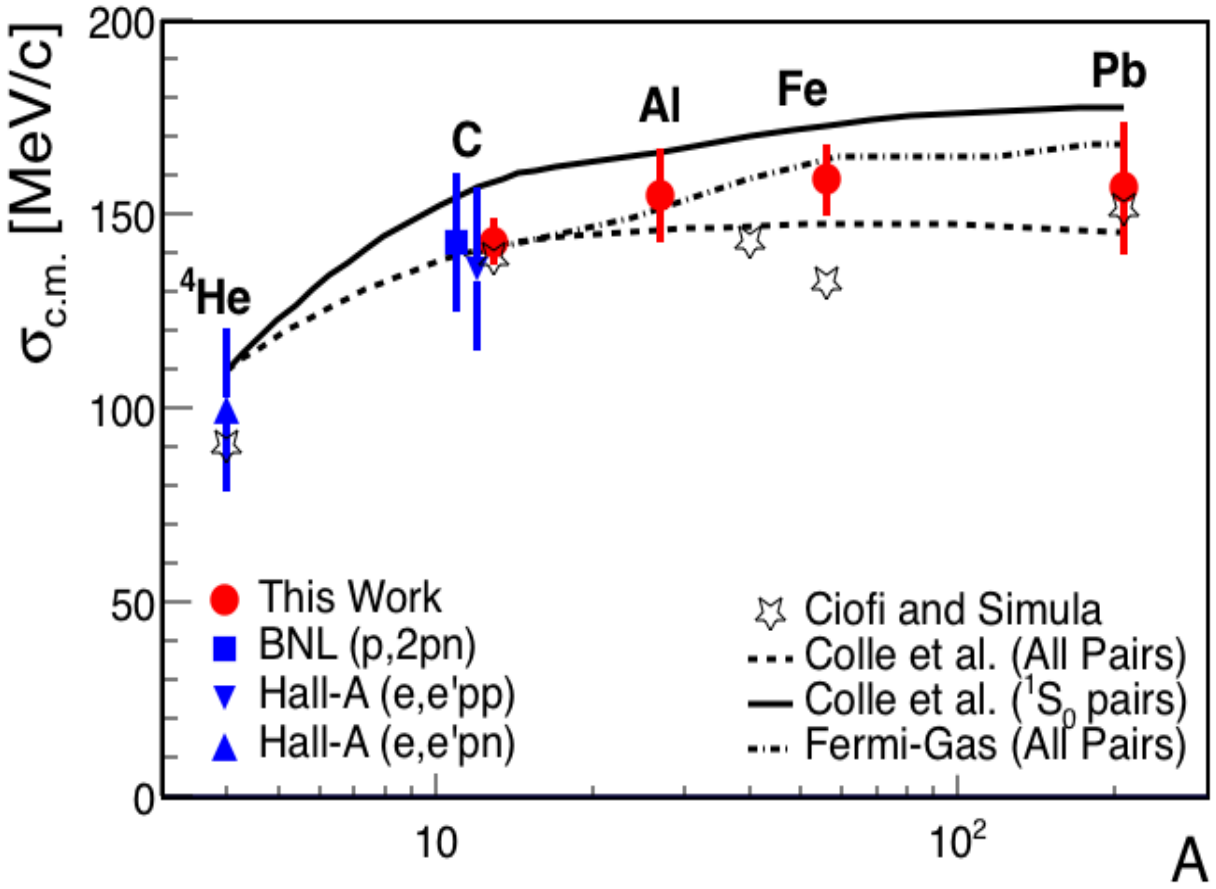


1000 – 2000 MeV

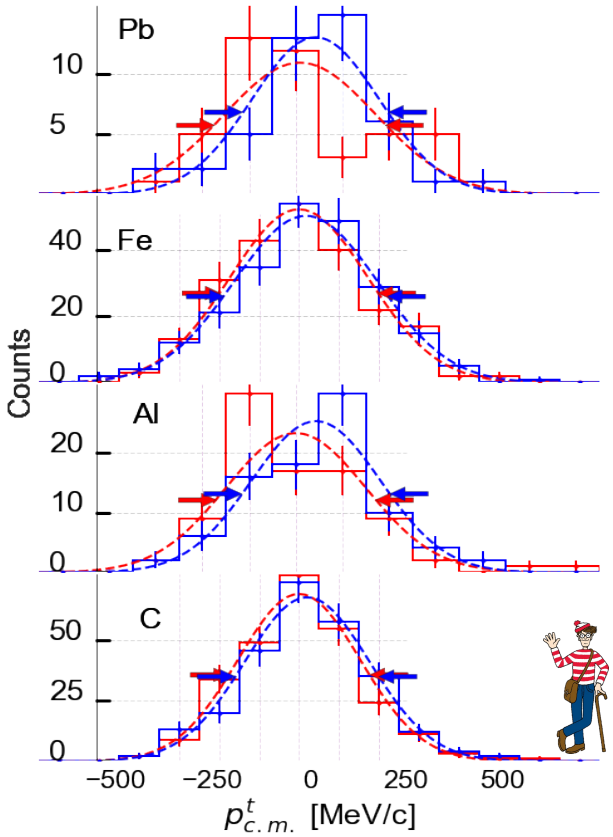
300 – 800 MeV/c

~ few MeV

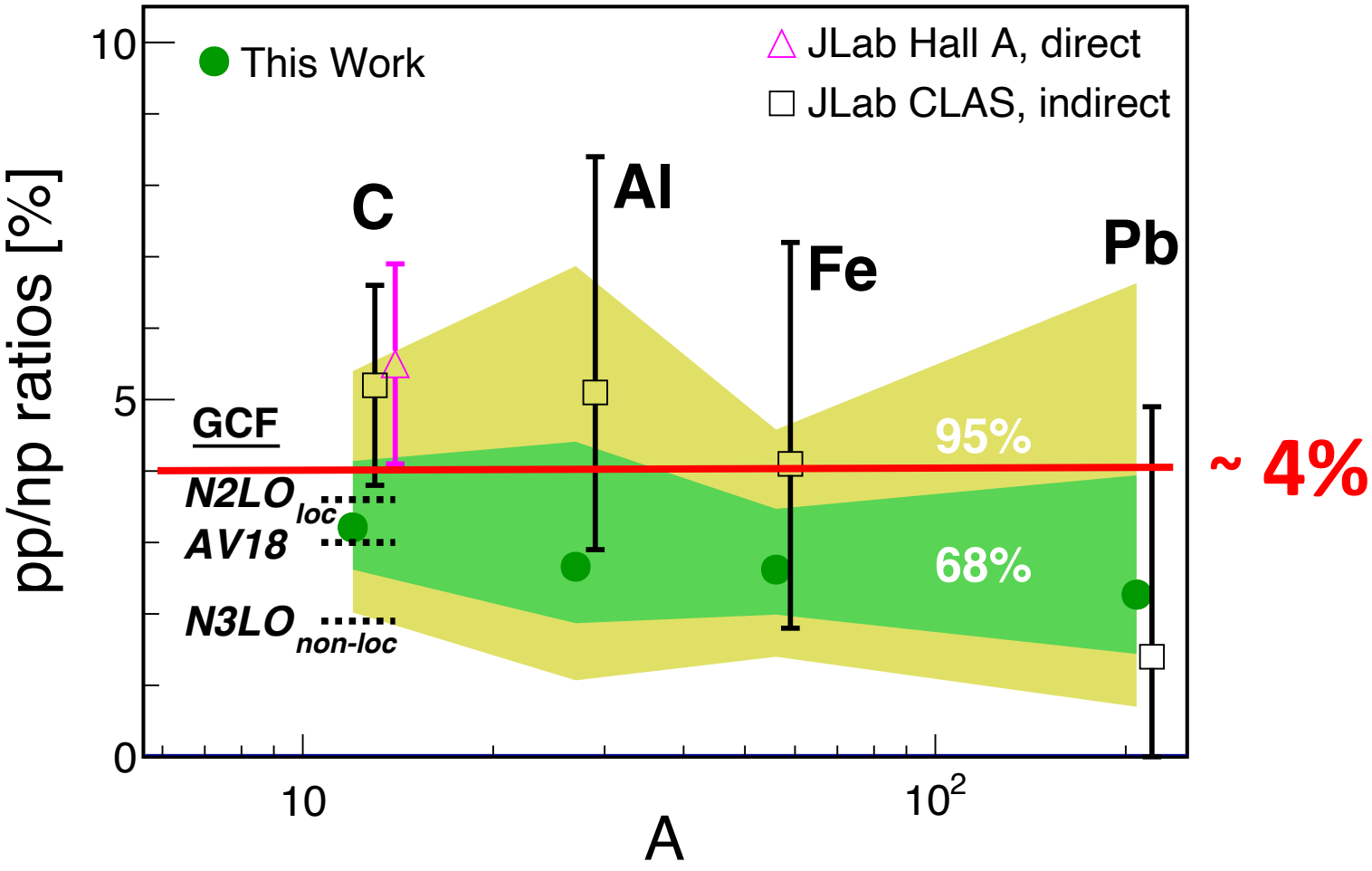
Mean-field Center-of-Mass Motion



Cohen, PRL (2018),
Korover, PRL (2014),
Shneor, PRL (2007),
Tang, PRL (2003).



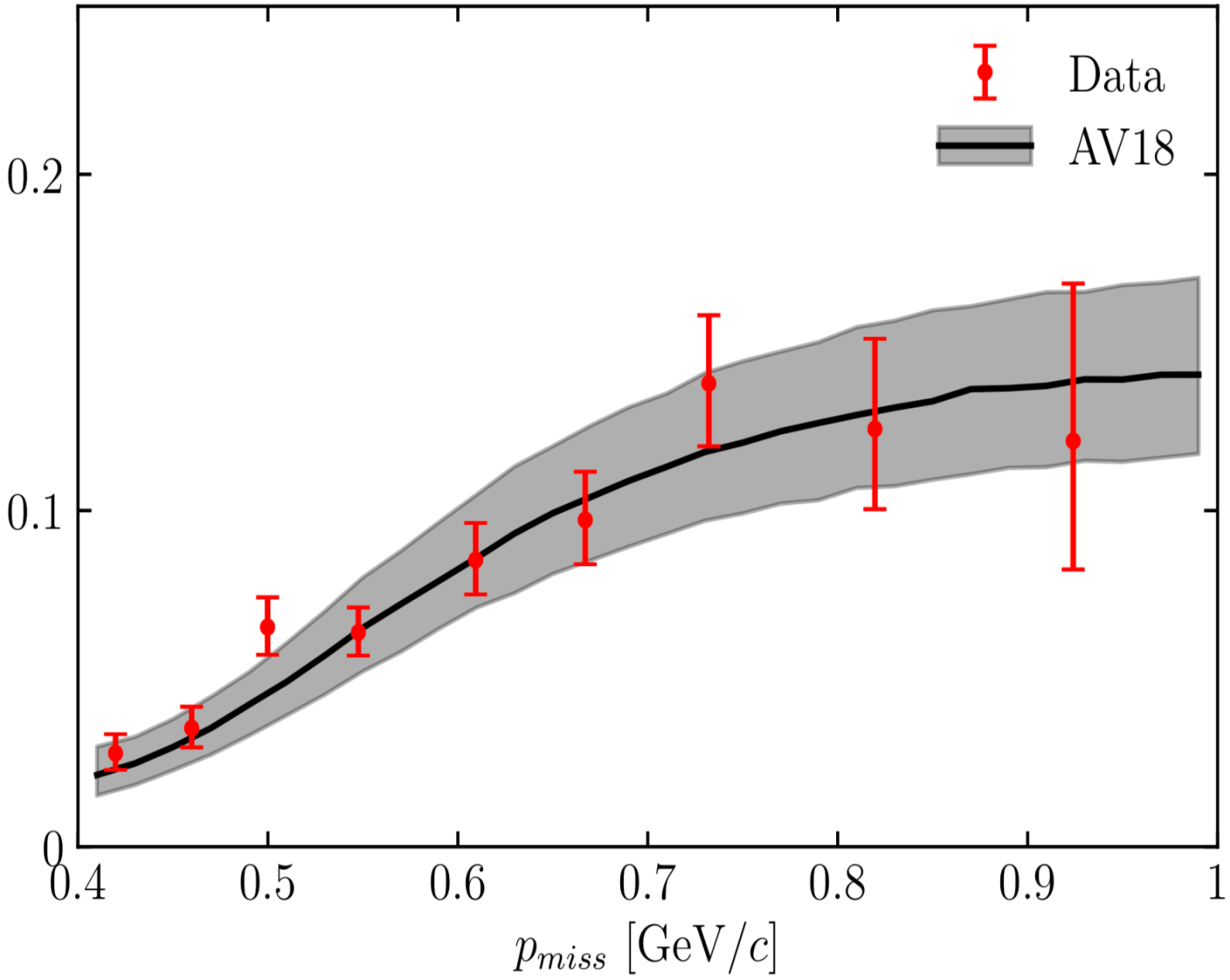
300 – 600 MeV/c: np pairs



Duer, PRL (2019); Duer, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003); Review: Hen RMP (2017);

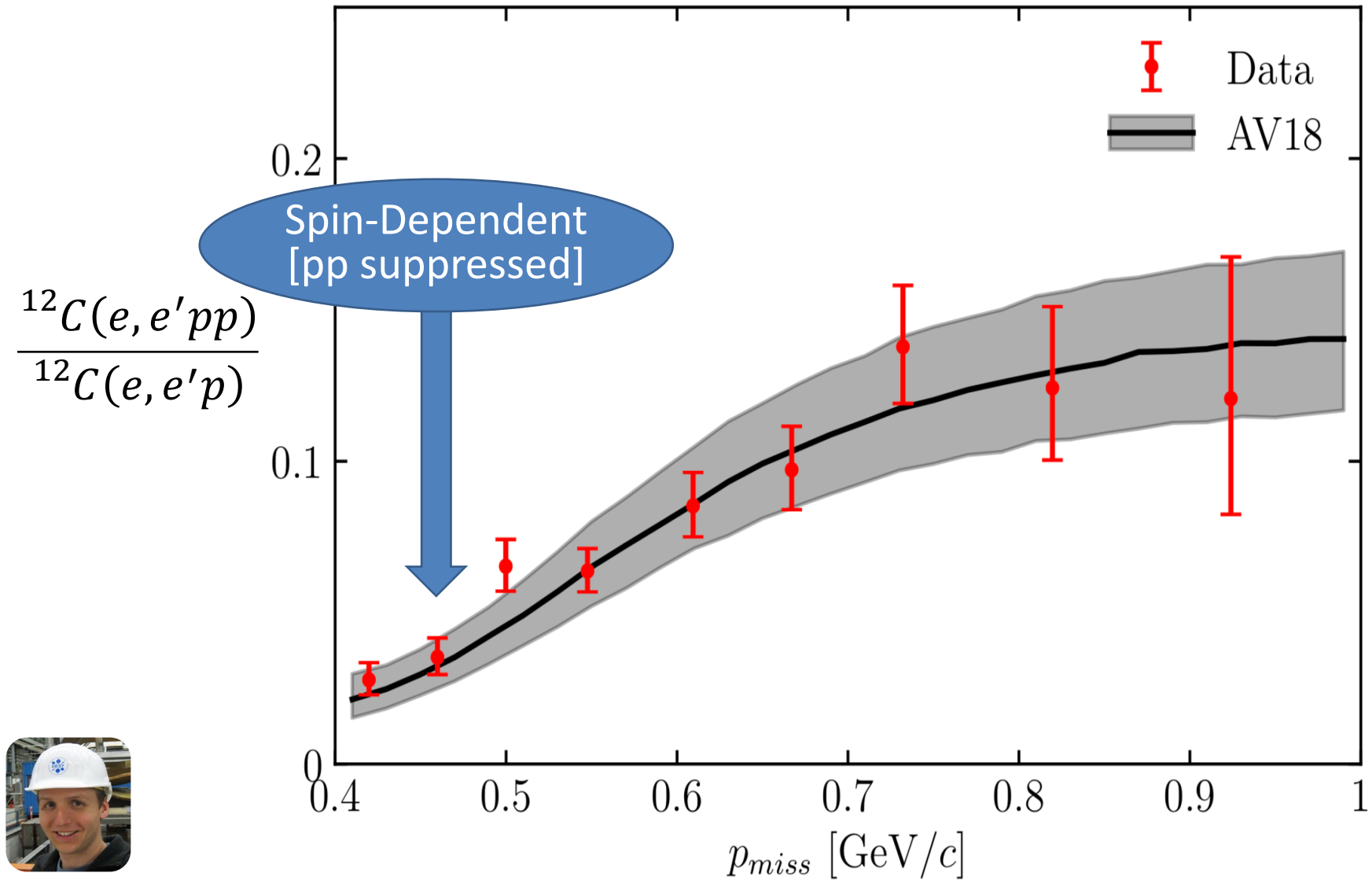
Reaching the Repulsive Core

$$\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)}$$



Schmidt et al., Nature (2020)

Reaching the Repulsive Core



Schmidt et al., Nature (2020)

Reaching the Repulsive Core

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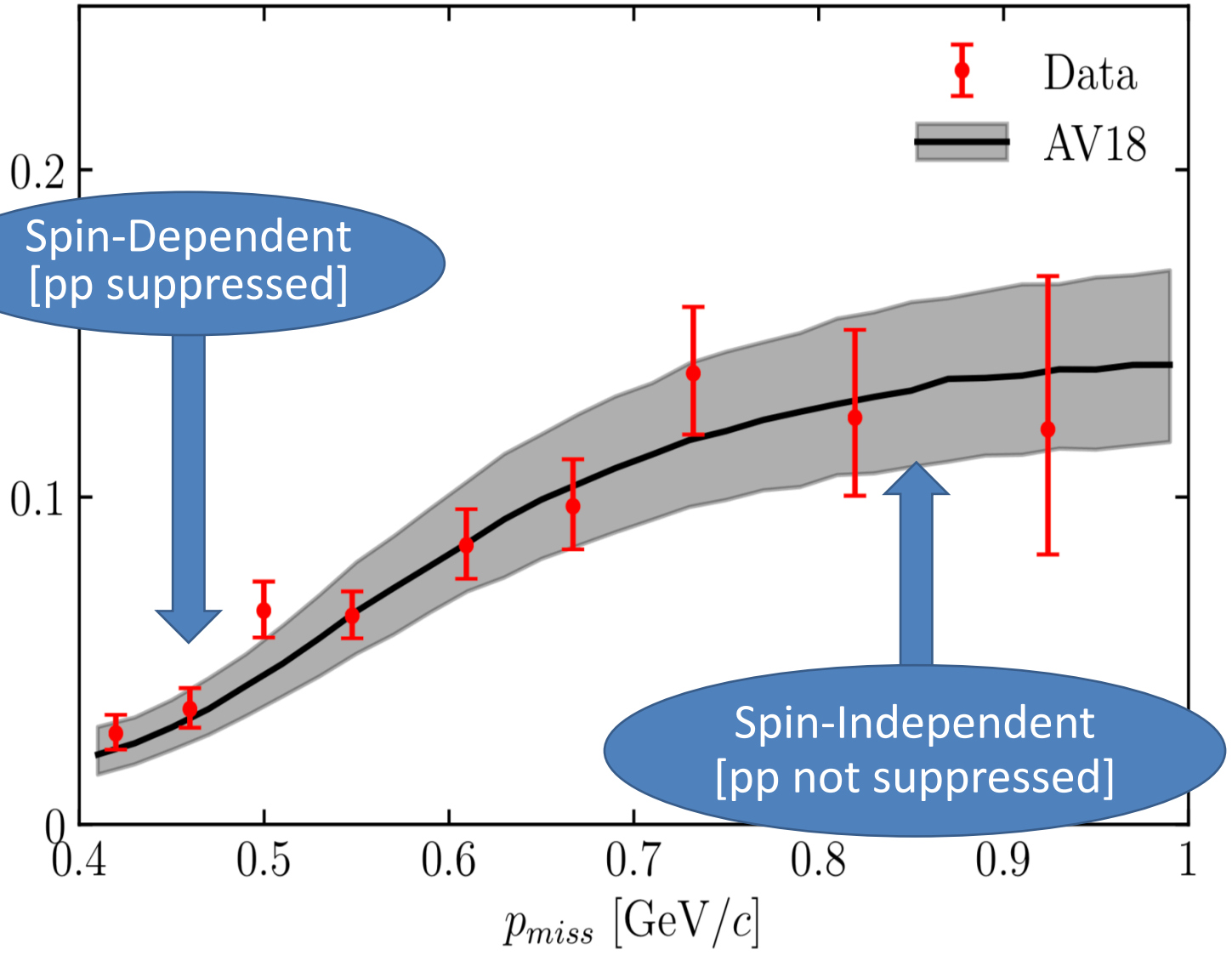
Schmidt et al., Nature (2020)



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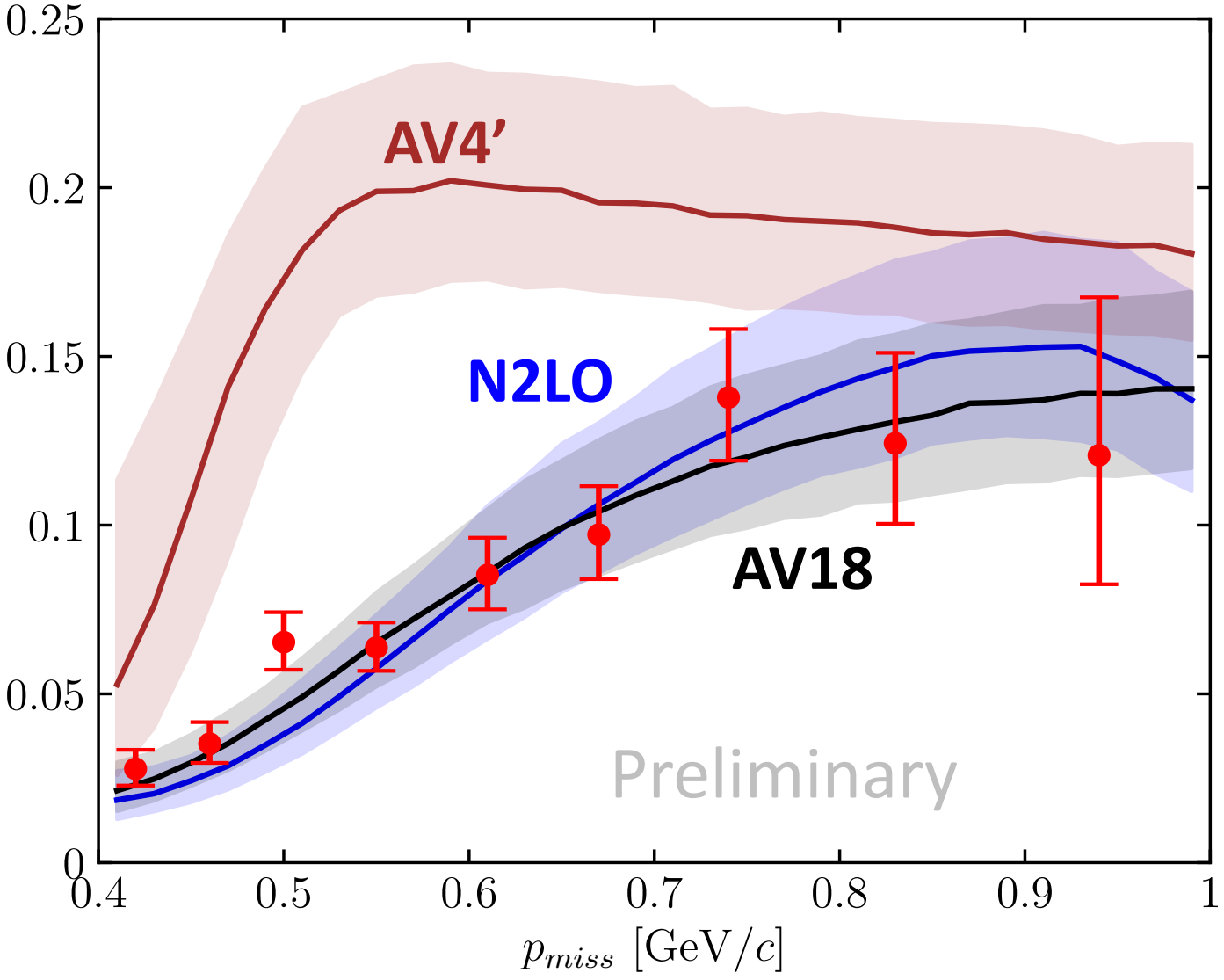
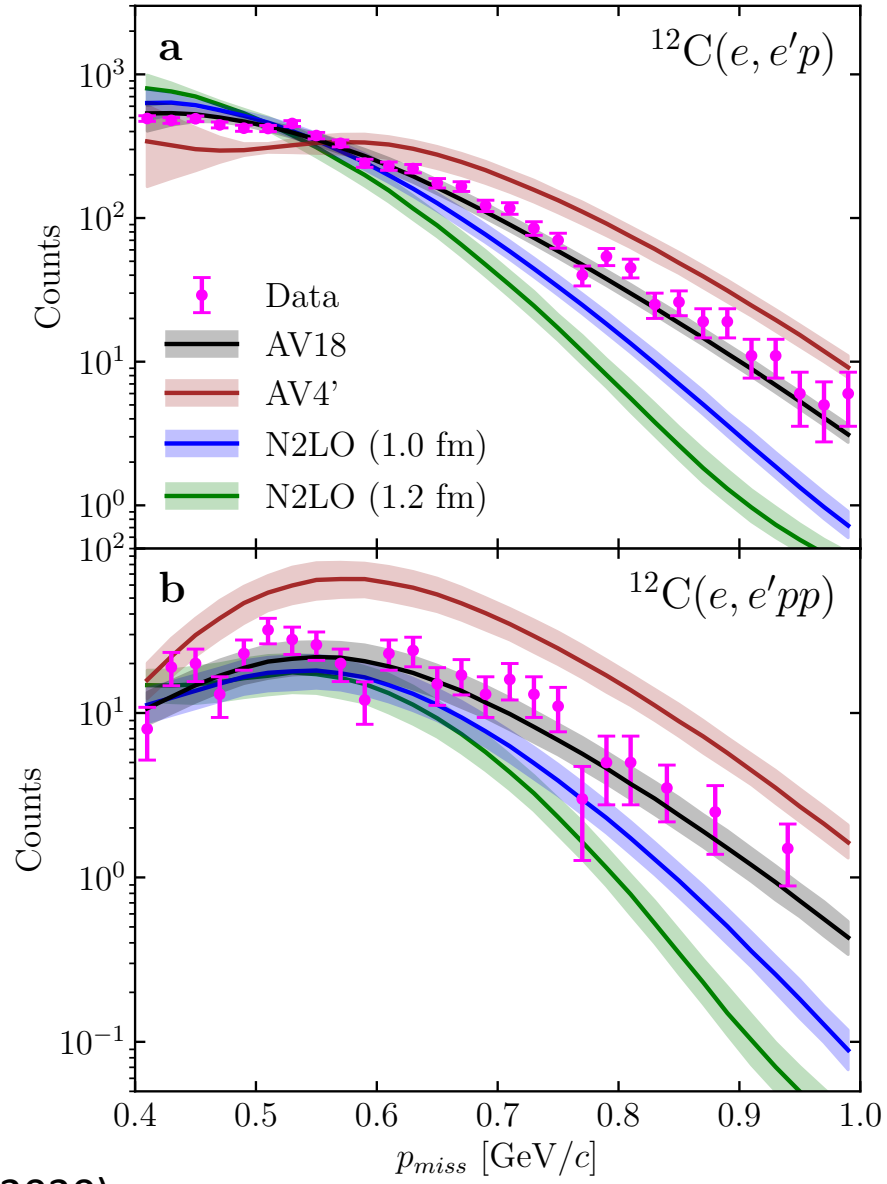


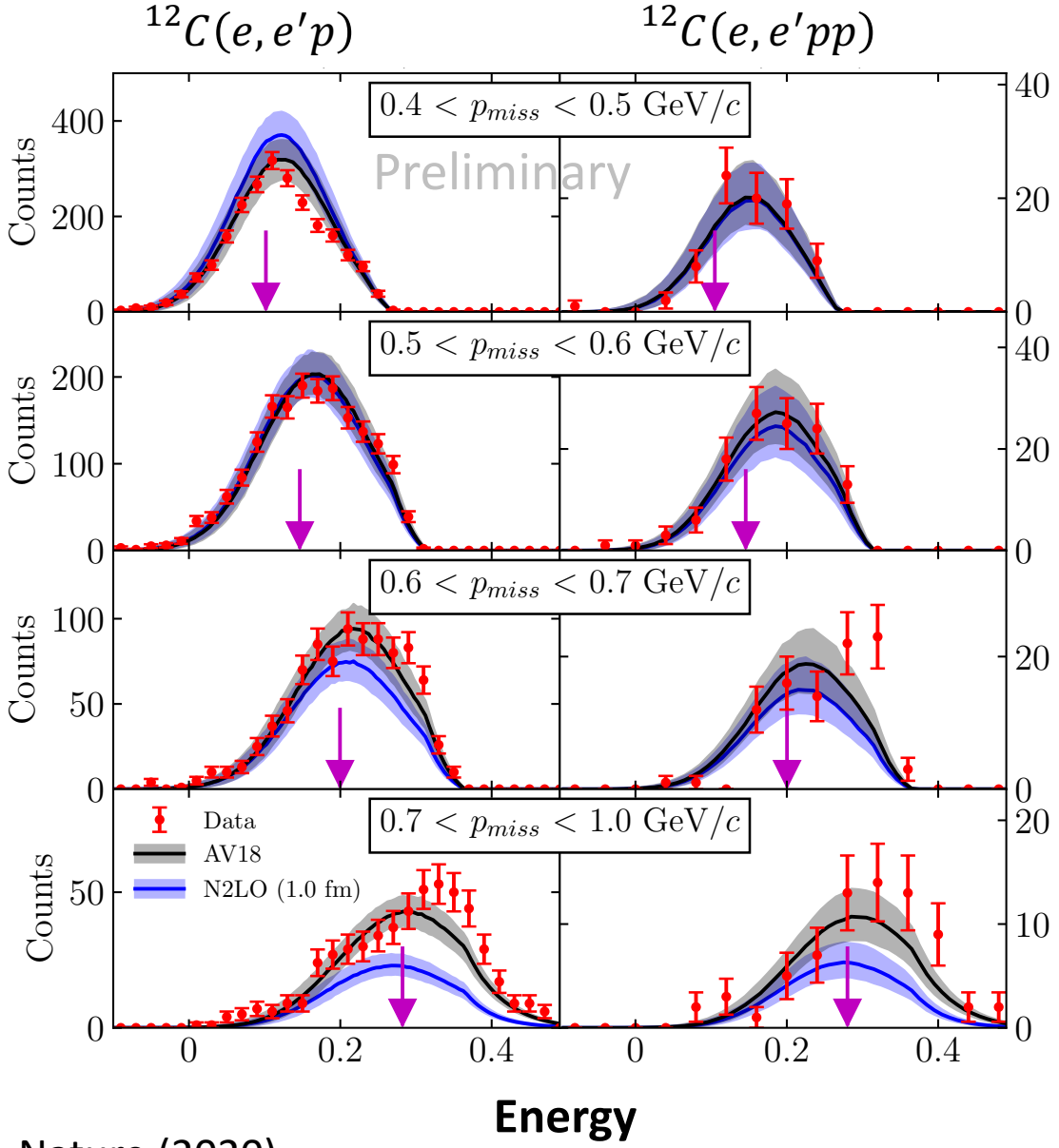
Schmidt et al., Nature (2020)

Nucleon Distributions Sensitivity



Schmidt et al., Nature (2020)

Spectral function Sensitivity



Momentum

400 – 500 MeV/c

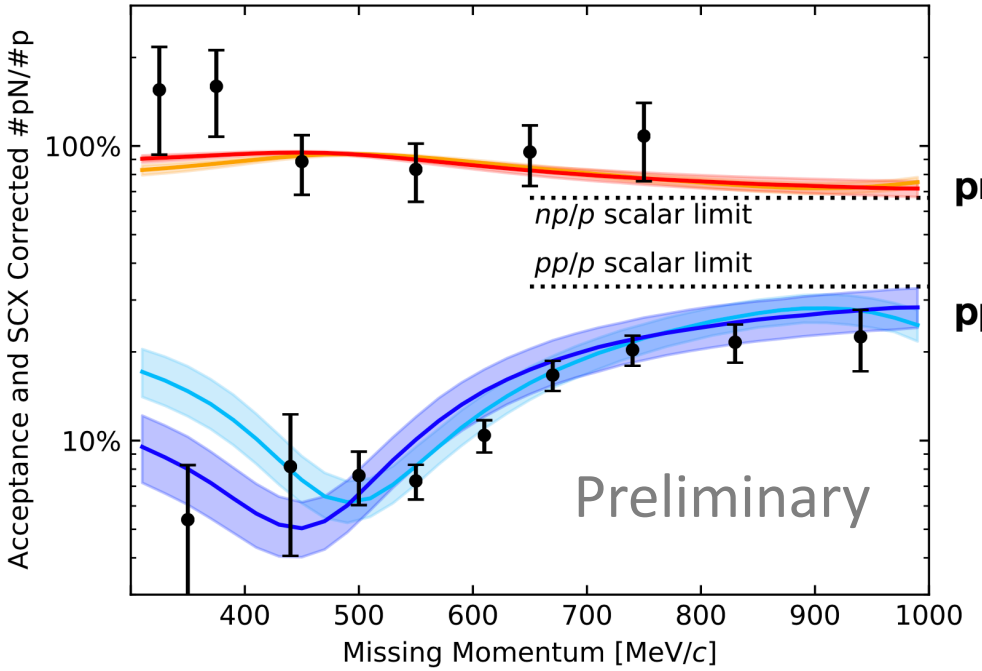
500 – 600 MeV/c

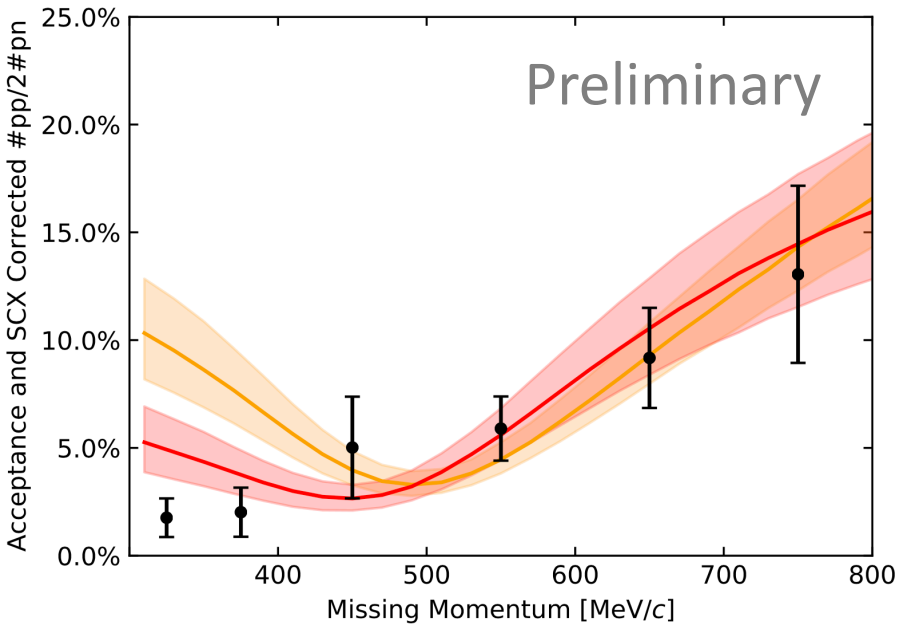
600 – 700 MeV/c

700 – 1000 MeV/c

Schmidt et al., Nature (2020)

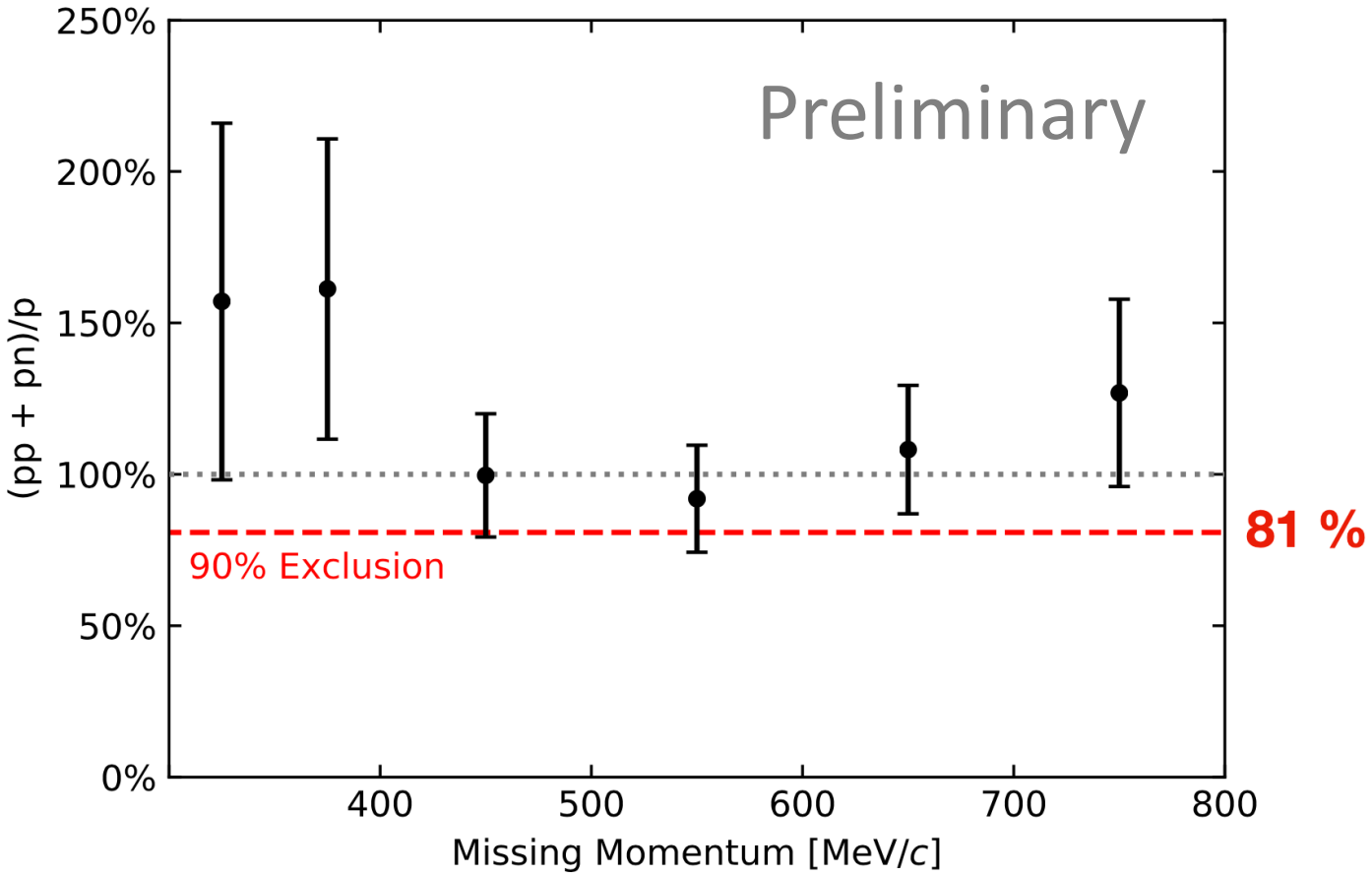
Neutron data consistency





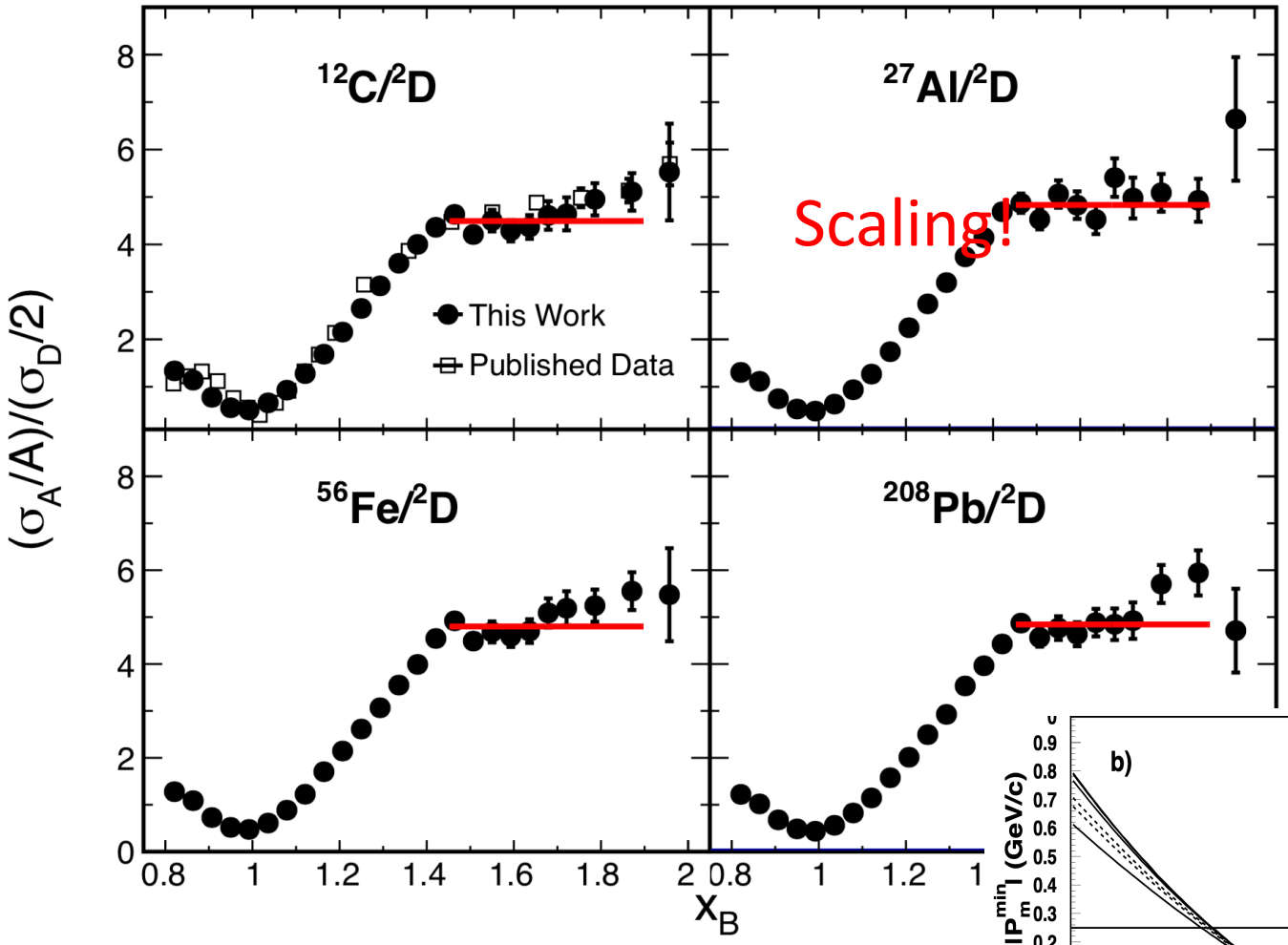
Korover et al., arXiv: 2004.07304 (2020)

Bound on SRC Dominance of high-p

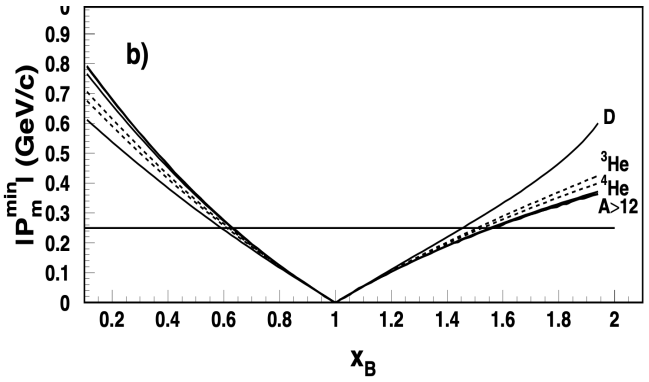


Korover et al., arXiv: 2004.07304 (2020)

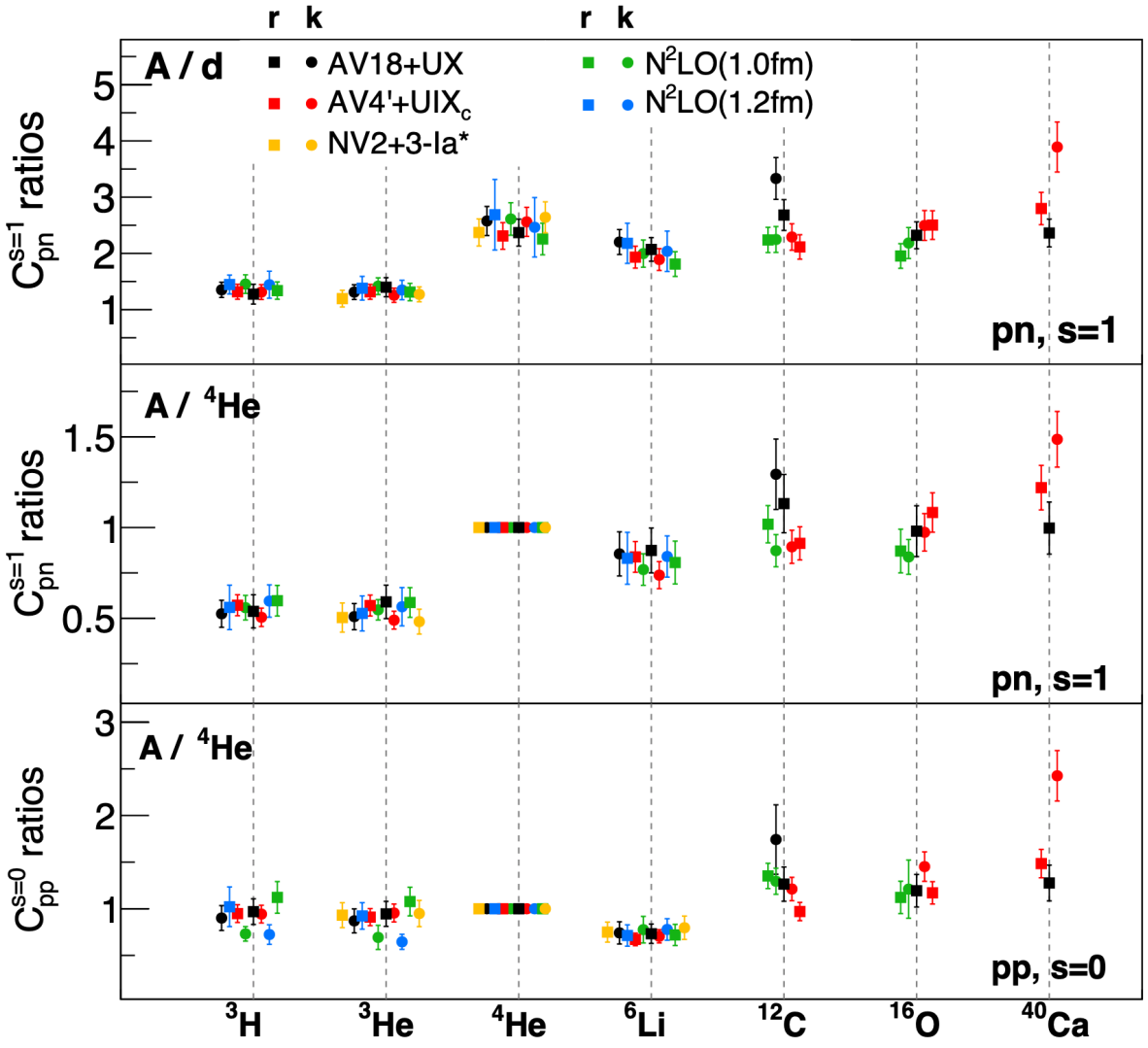
High-Momentum Scaling



Schmookler, Duer, Schmidt et al., (2018)



Contacts are ***universal***!



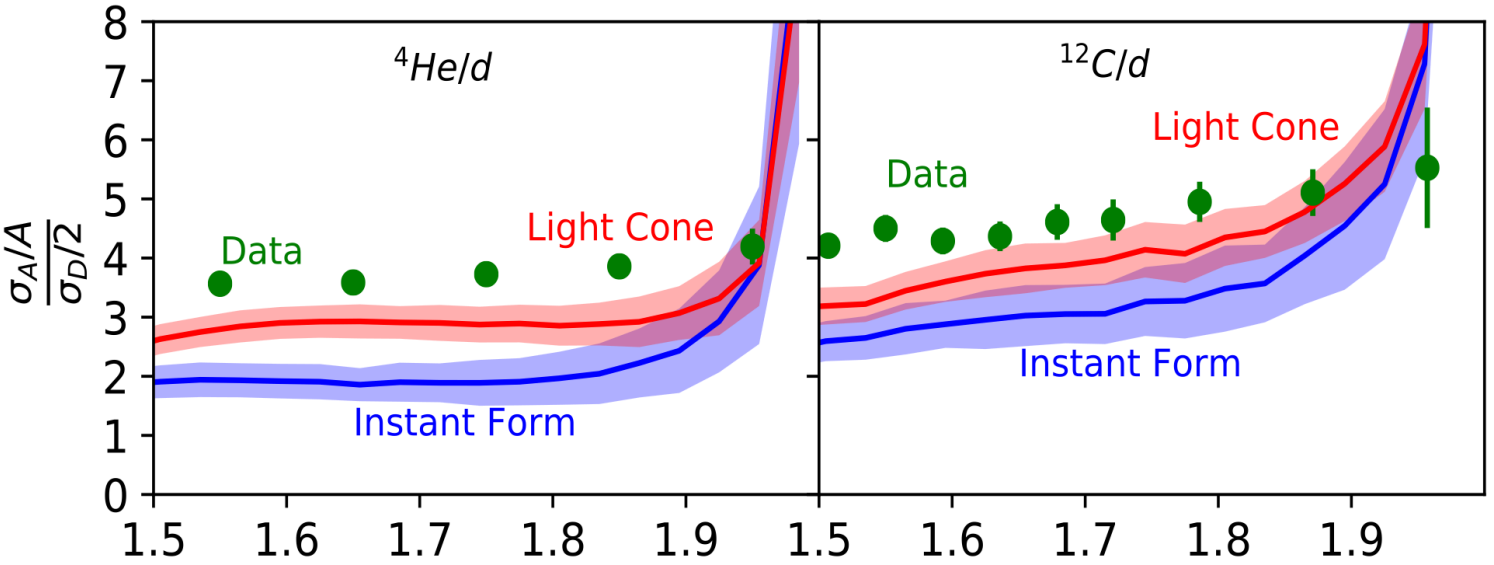
Scaling of SRC pairs in different nuclei is driven by mean-field physics.

Same for all NN interactions!
Same for small-r and high-k!

*also seen for small-r by Chen & Lynn et al.

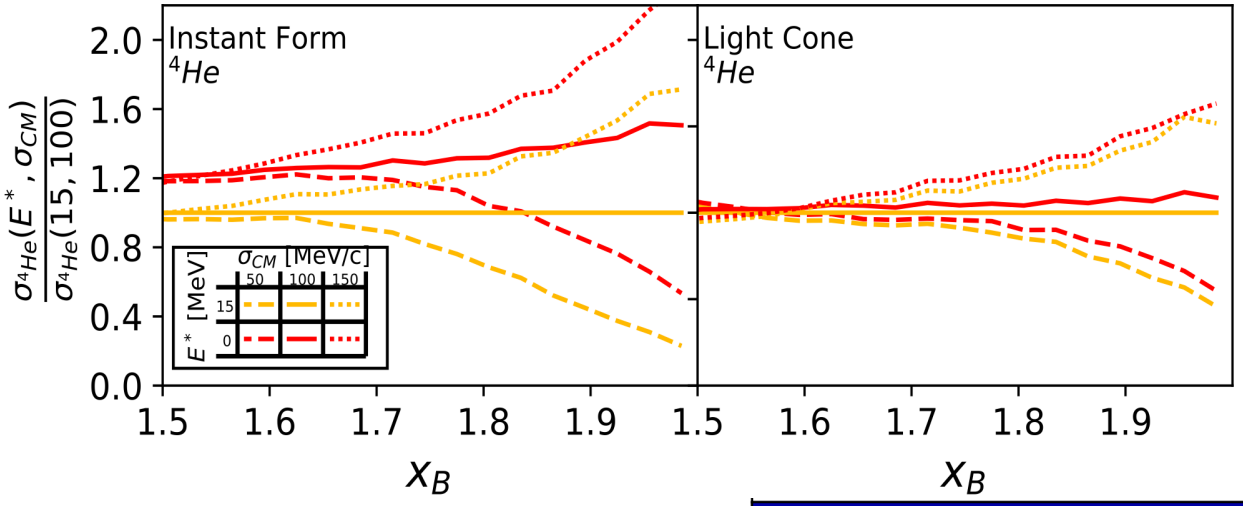
Cruz Torres et al., Nature Physics (2020)

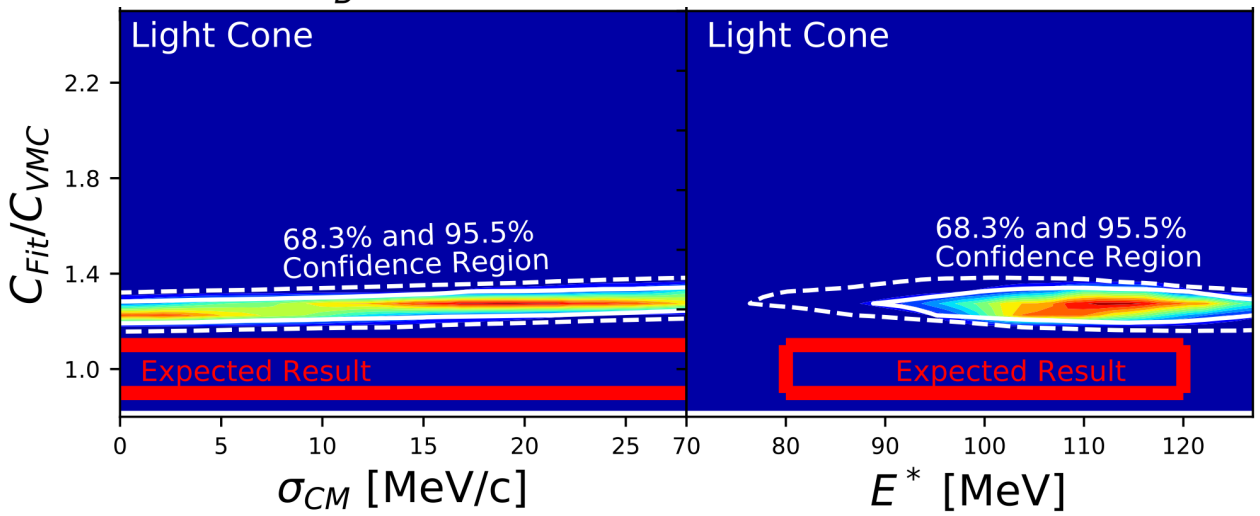
Theory that works for (e,e'NN) struggles for (e,e')



Weiss and Denniston et al., arXiv: 2005.01621 (2020)

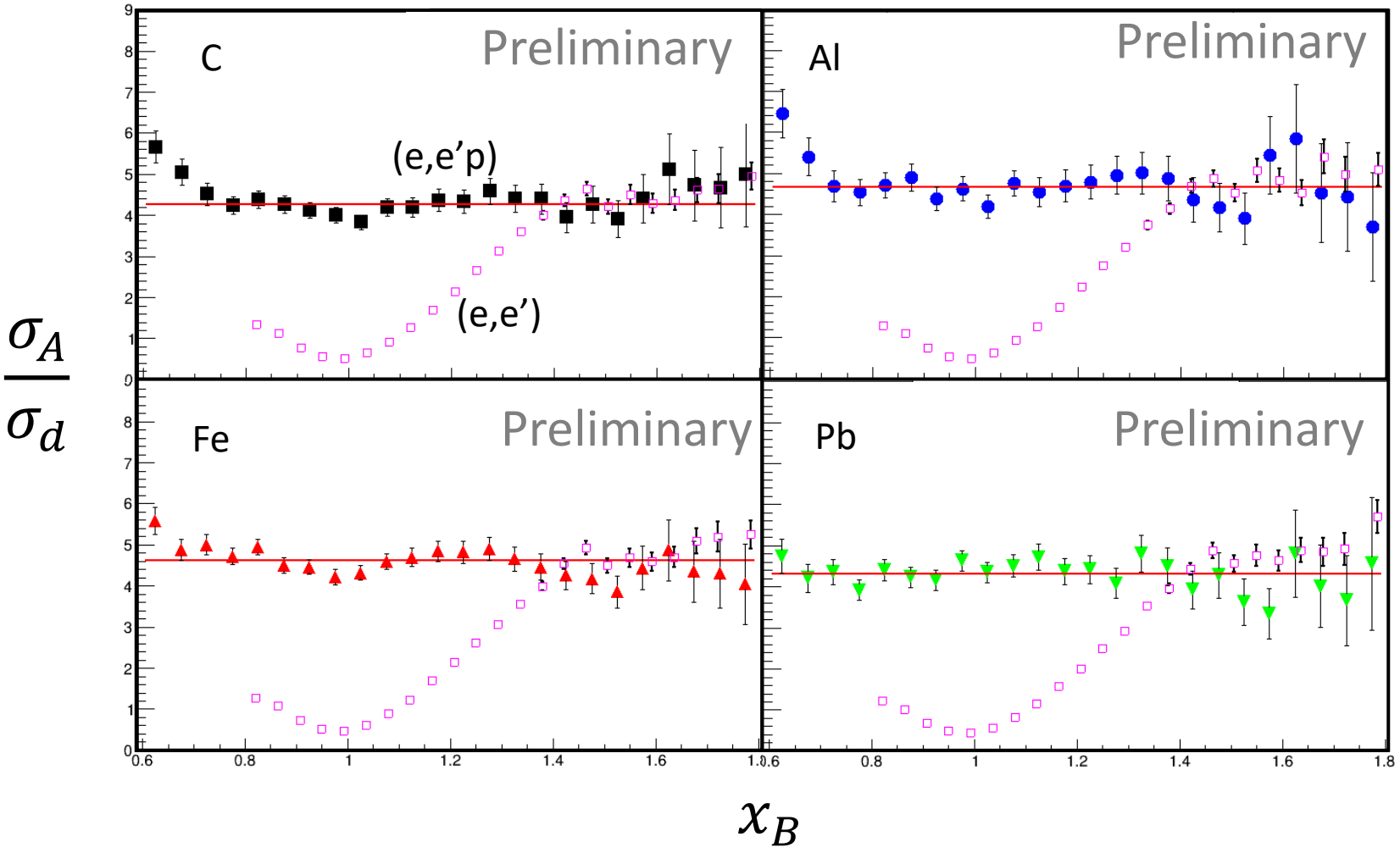
Need to re-think our *quantitative* interpretation?





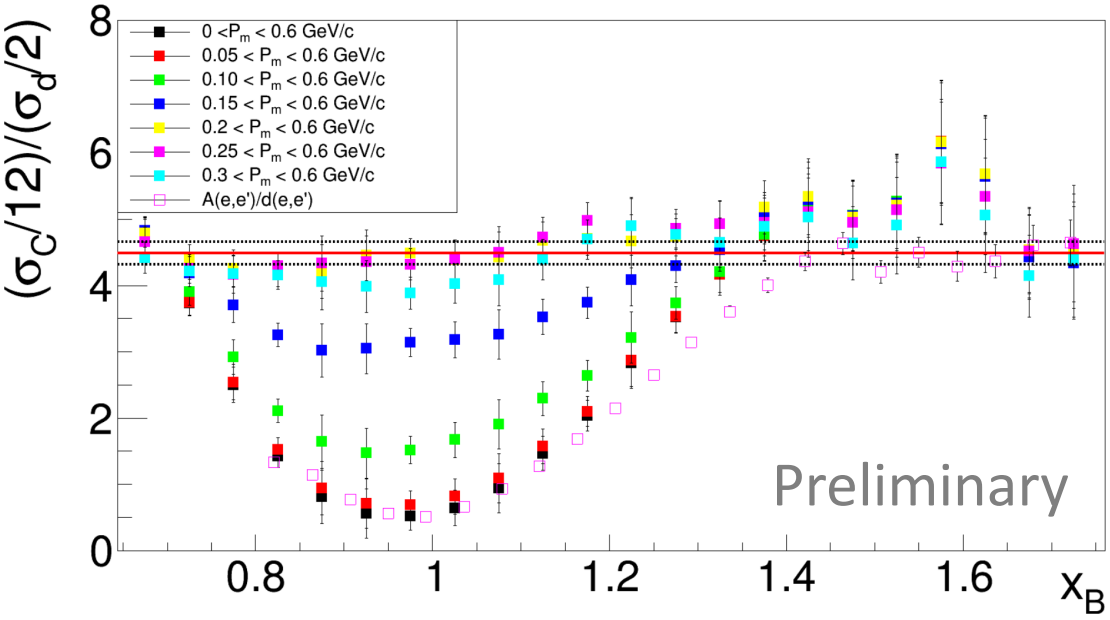
Weiss and Denniston et al., arXiv: 2005.01621 (2020)

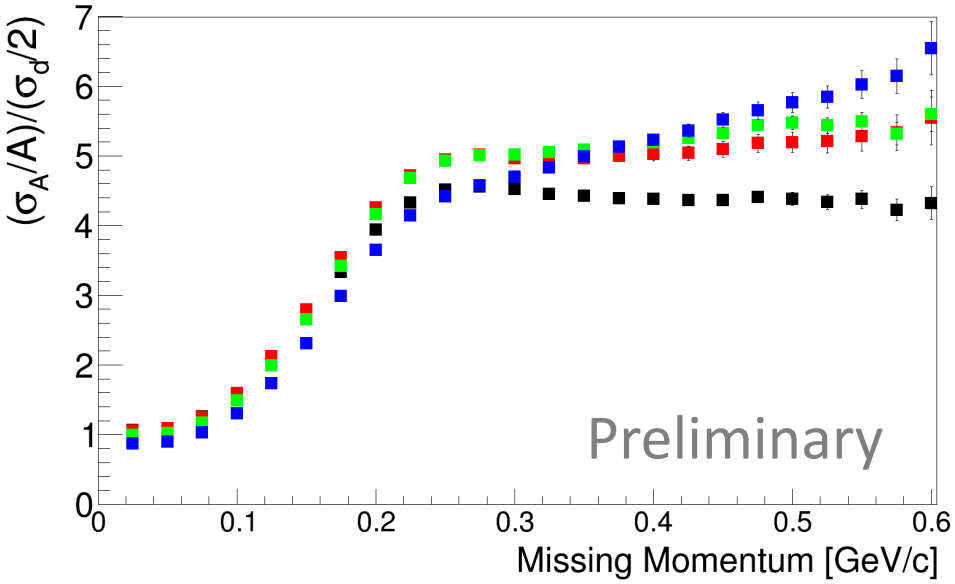
(e,e'p) to the rescue!



Korover and Denniston et al.

SRC Dominance Onset ~ k_F





Korover and Denniston et al.

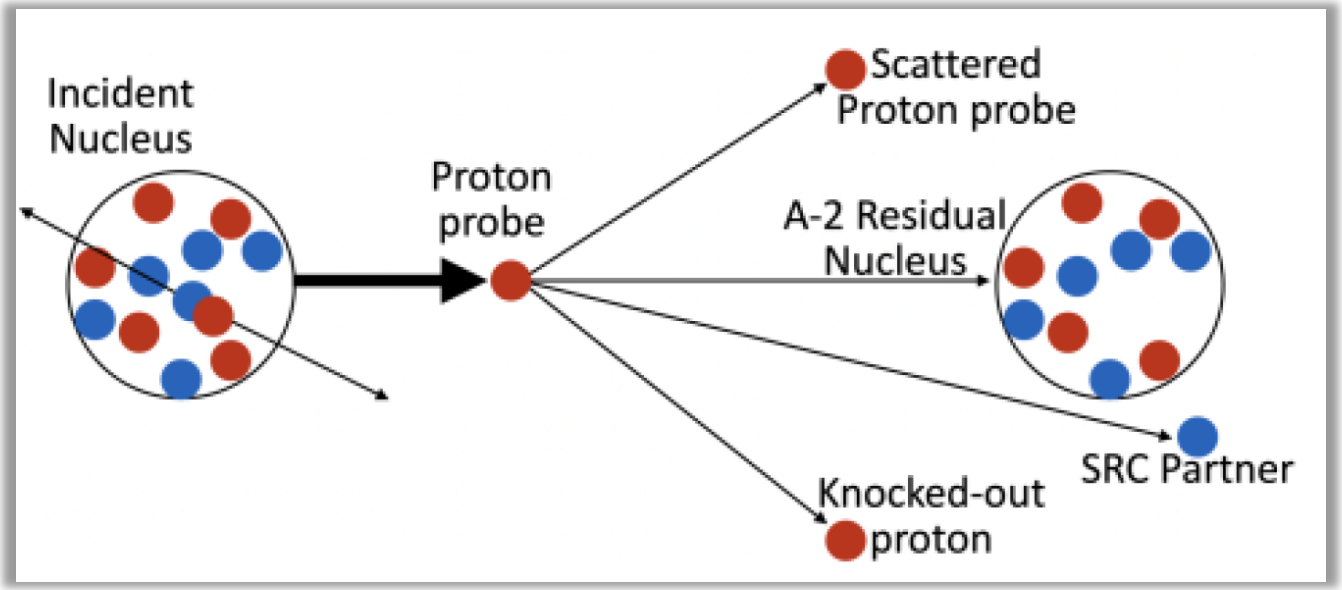
1. JLab
   - (e,e’NN): NN interaction
   - (e,e’): Pair abundances

2. JINR
   - (p,2p A-2)n: fully exclusive SRCs

3. Neutron Rich Systems
   - Insight from (e,e’N)
   - Interpretability of (e,e’)

Going Inverse:

Towards Colliders & Radioactive Beams



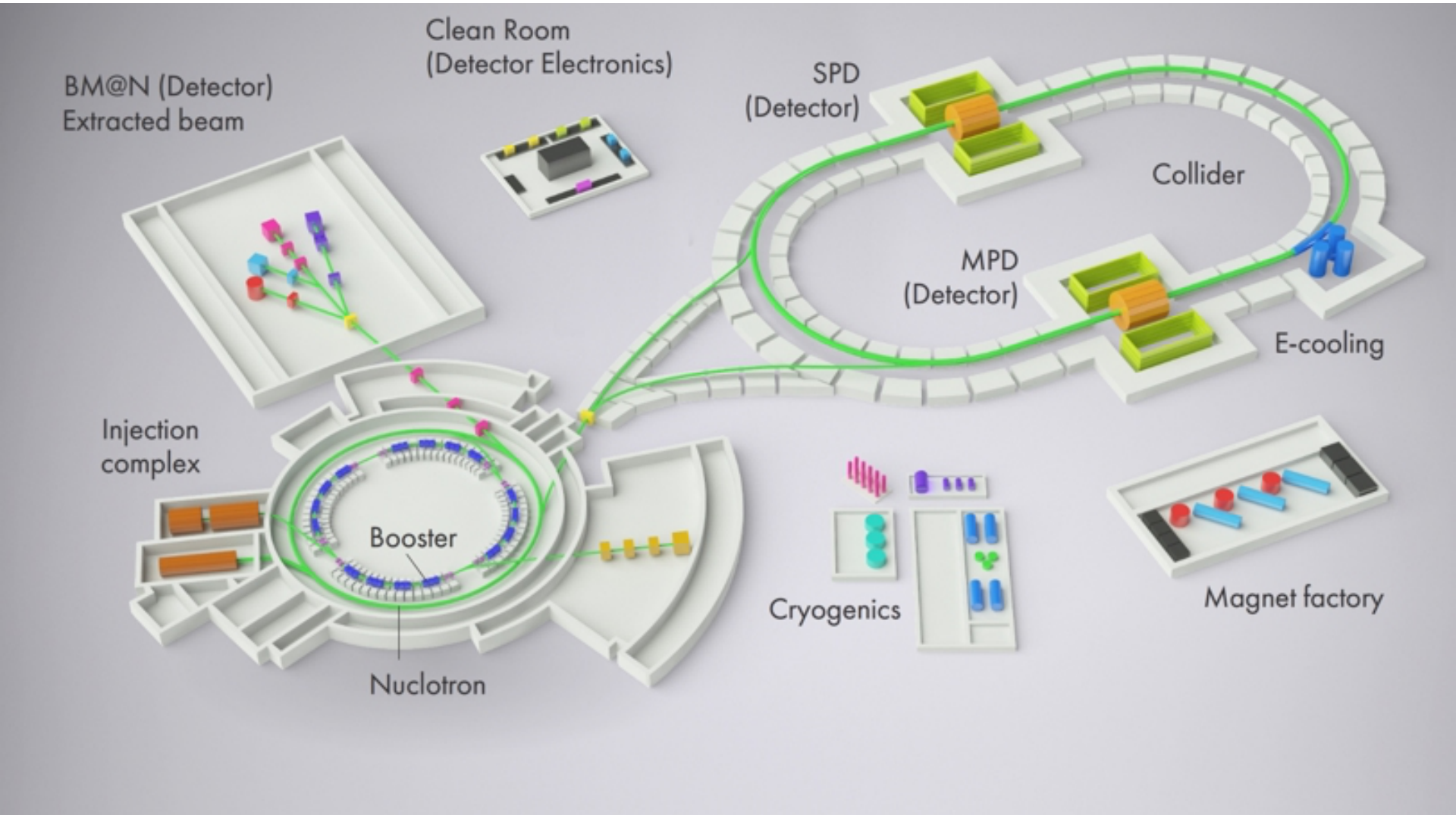
Scale Separation

Factorization of SRC distribution function:

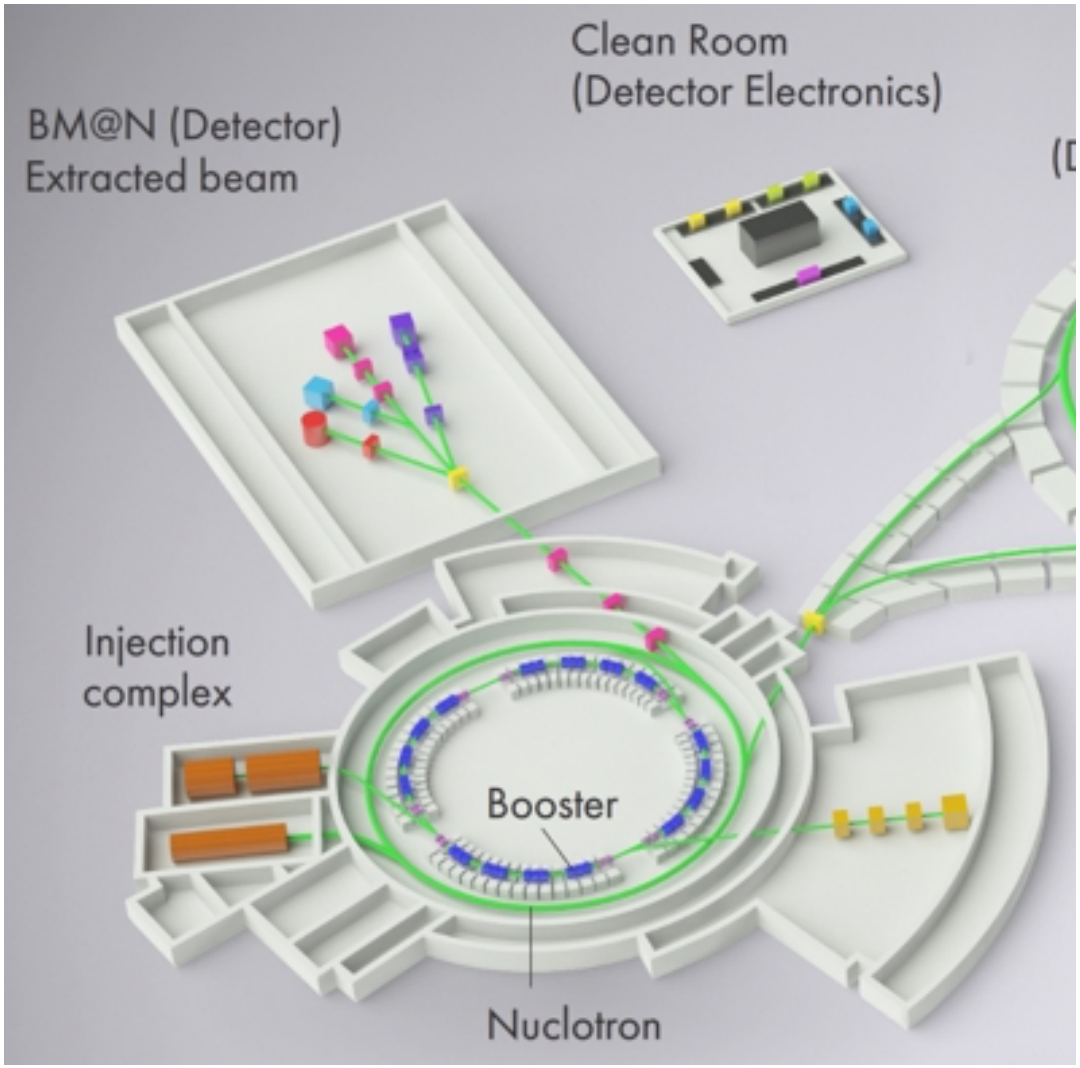
$$f\left(p_{rel}, p_{c.m.}, \theta_{rel,c.m.}\right) \approx C(p_{c.m.}) \times \varphi(p_{rel})$$

Constant (Low-Energy) x Two-body (High-Energy)

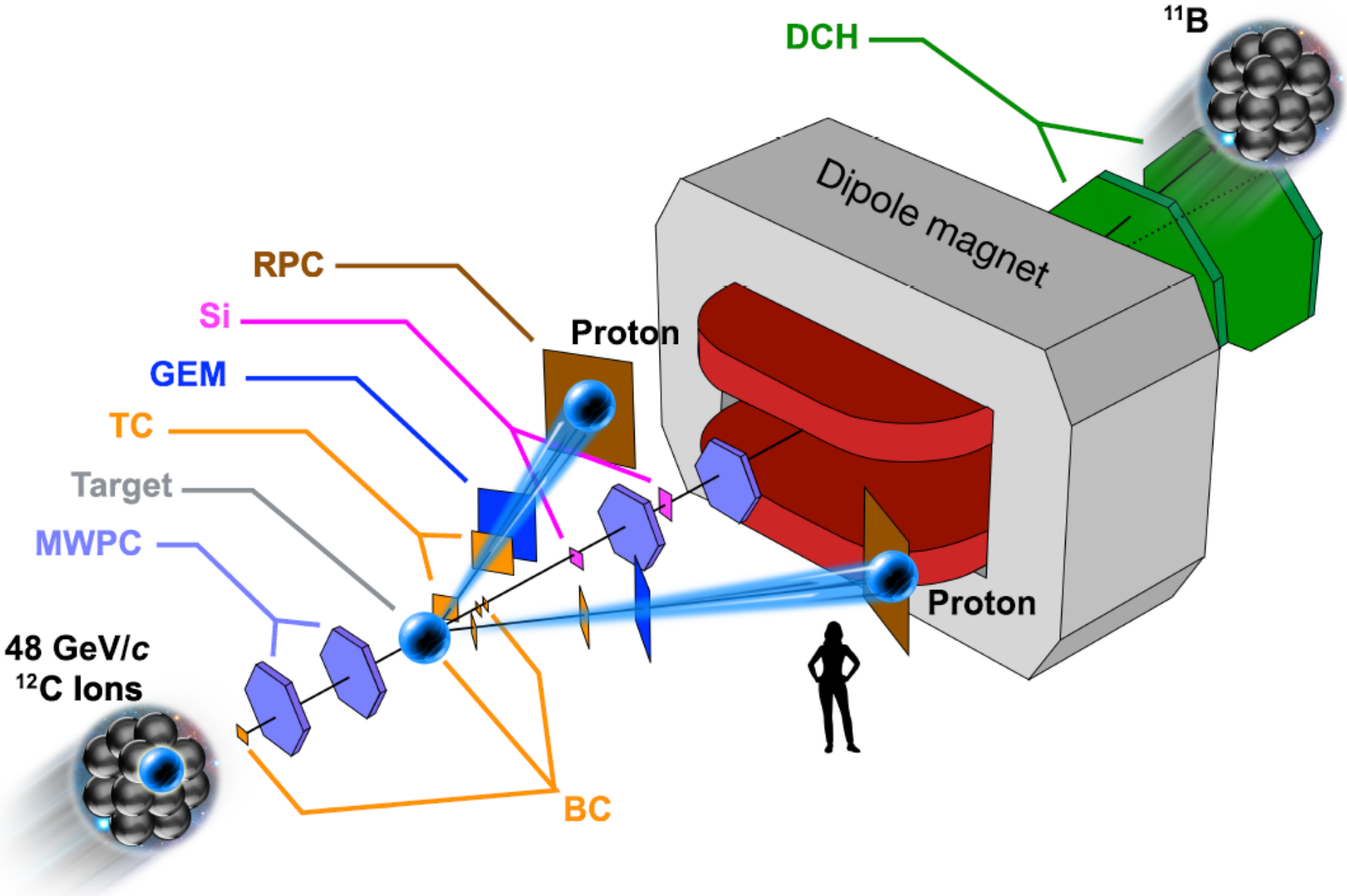
High-Energy Ion Beam @ JINR Nuclotron

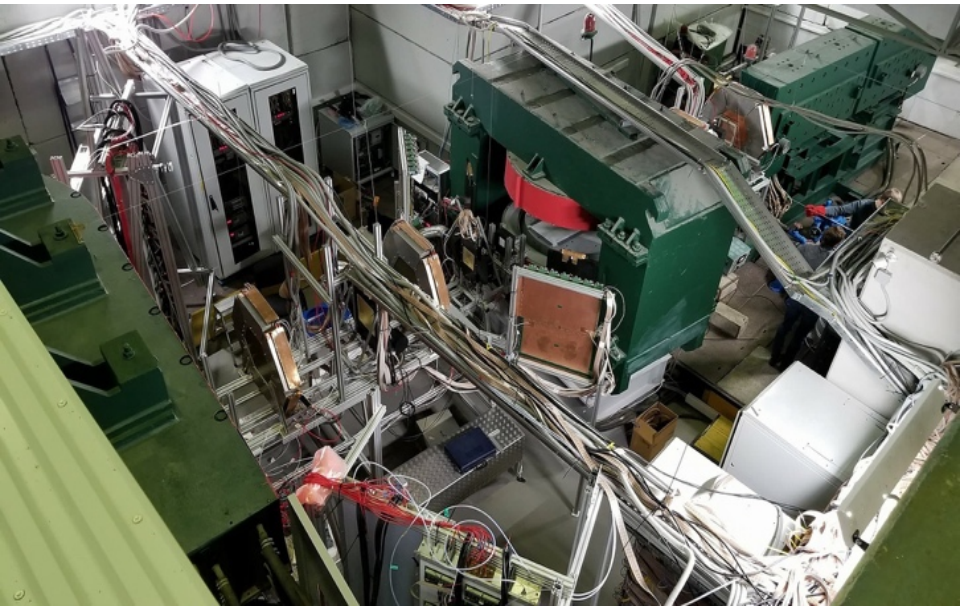


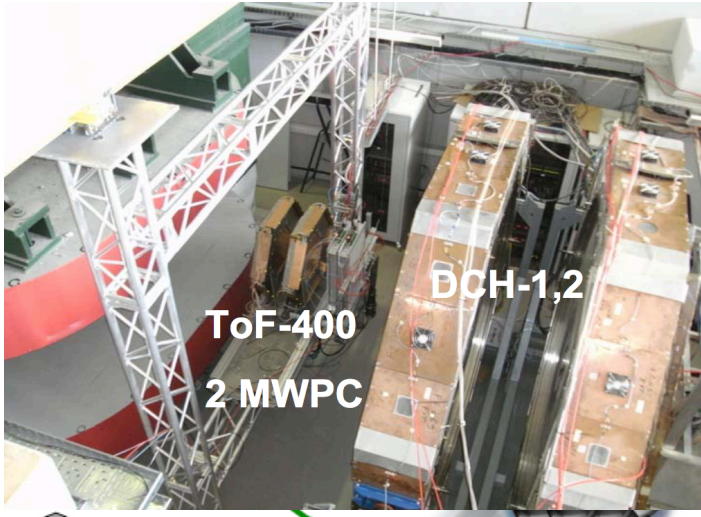
High-Energy Ion Beam @ JINR Nuclotron

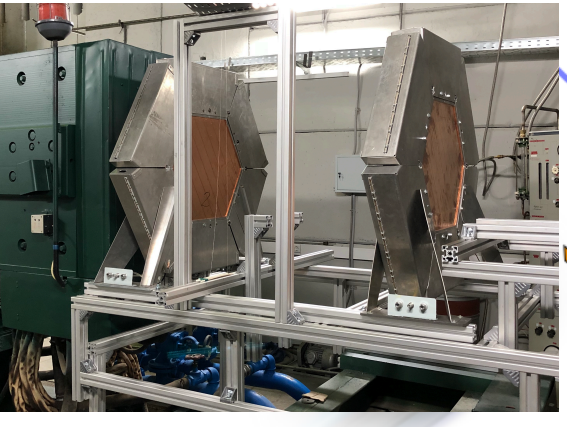


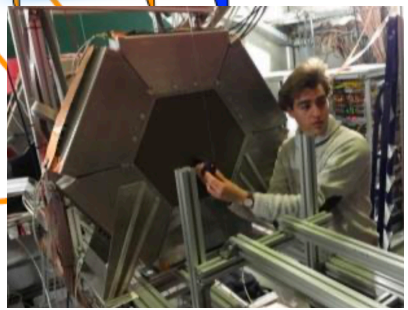
SRC @ BM@N

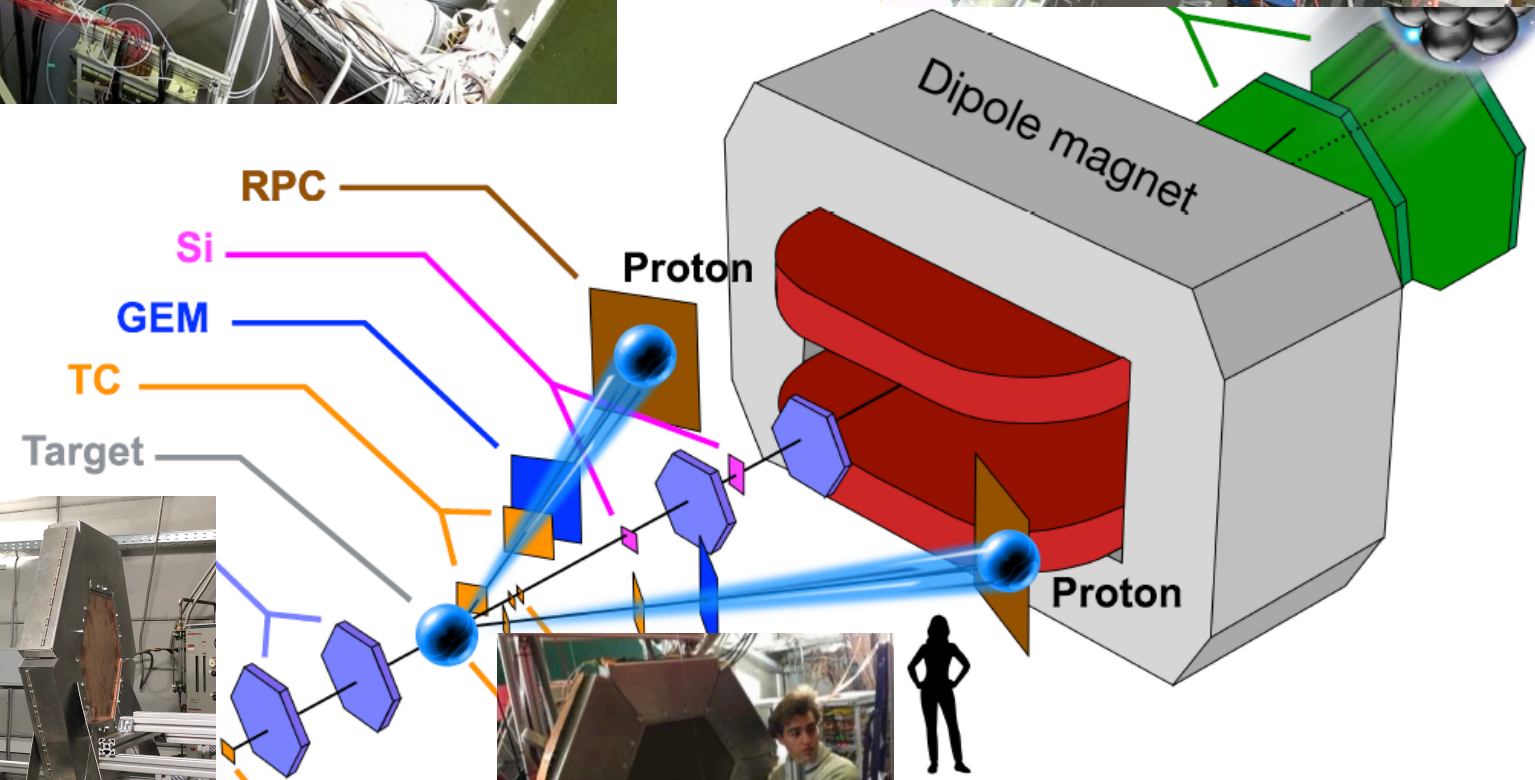

DCH
^{11}B
Dipole magnet
RPC
Si
GEM
TC
Target
MWPC
Proton
Proton
48 GeV/c
^{12}C Ions
BC



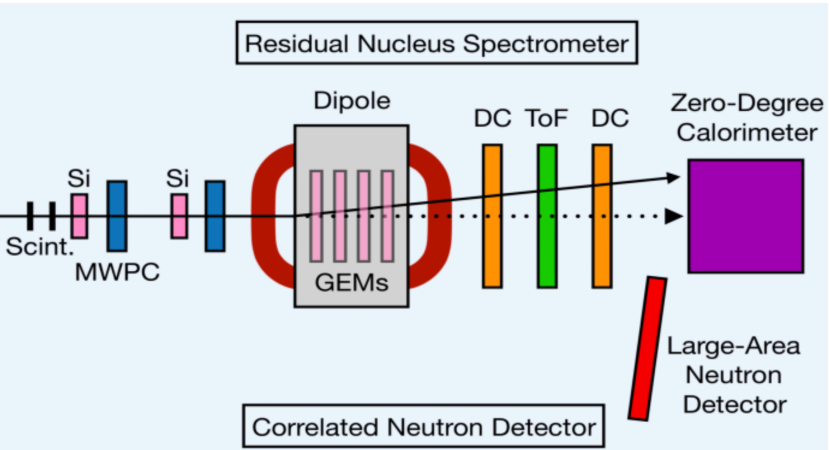

ToF-400
2 MWPC
DCH-1,2

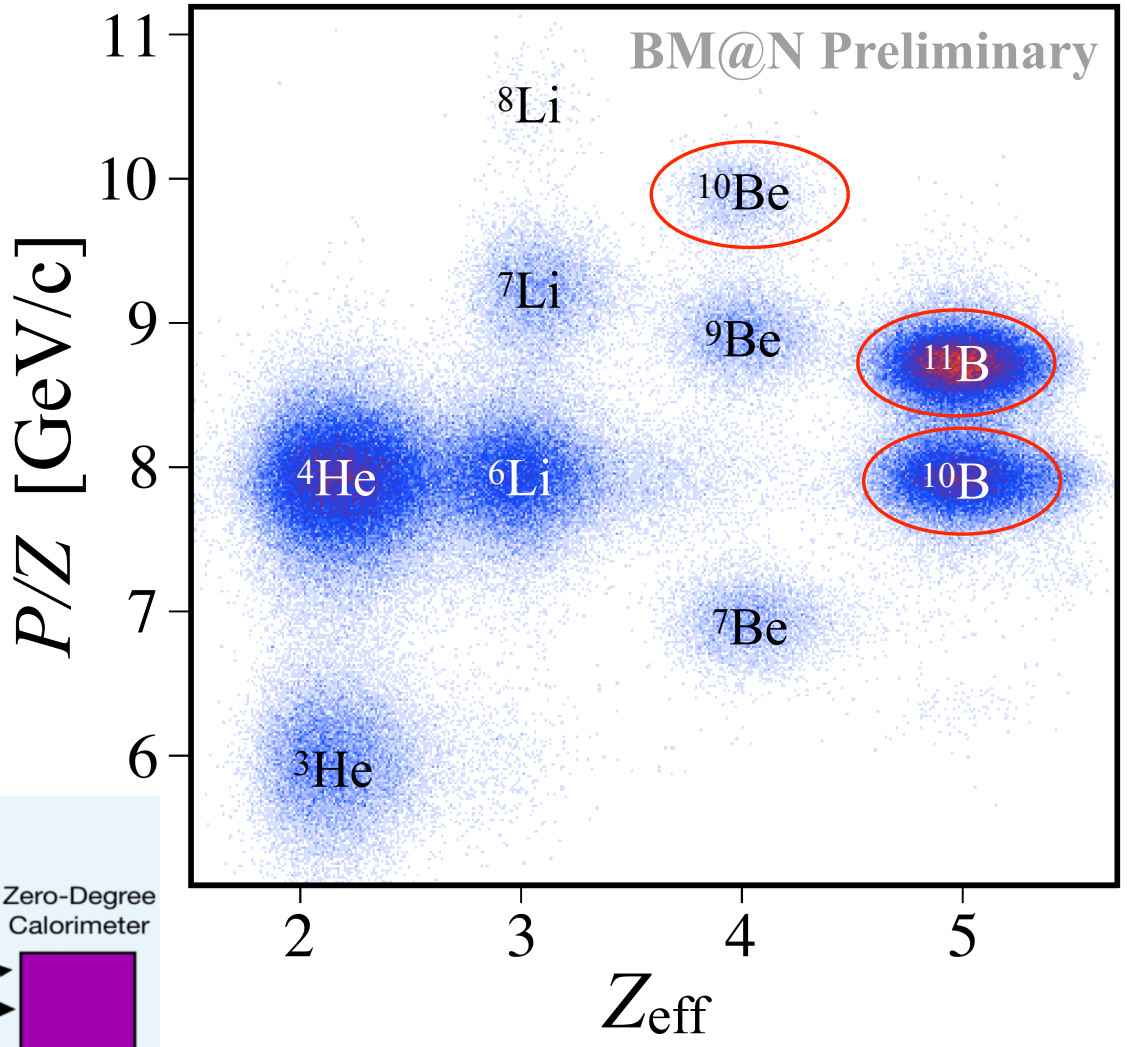




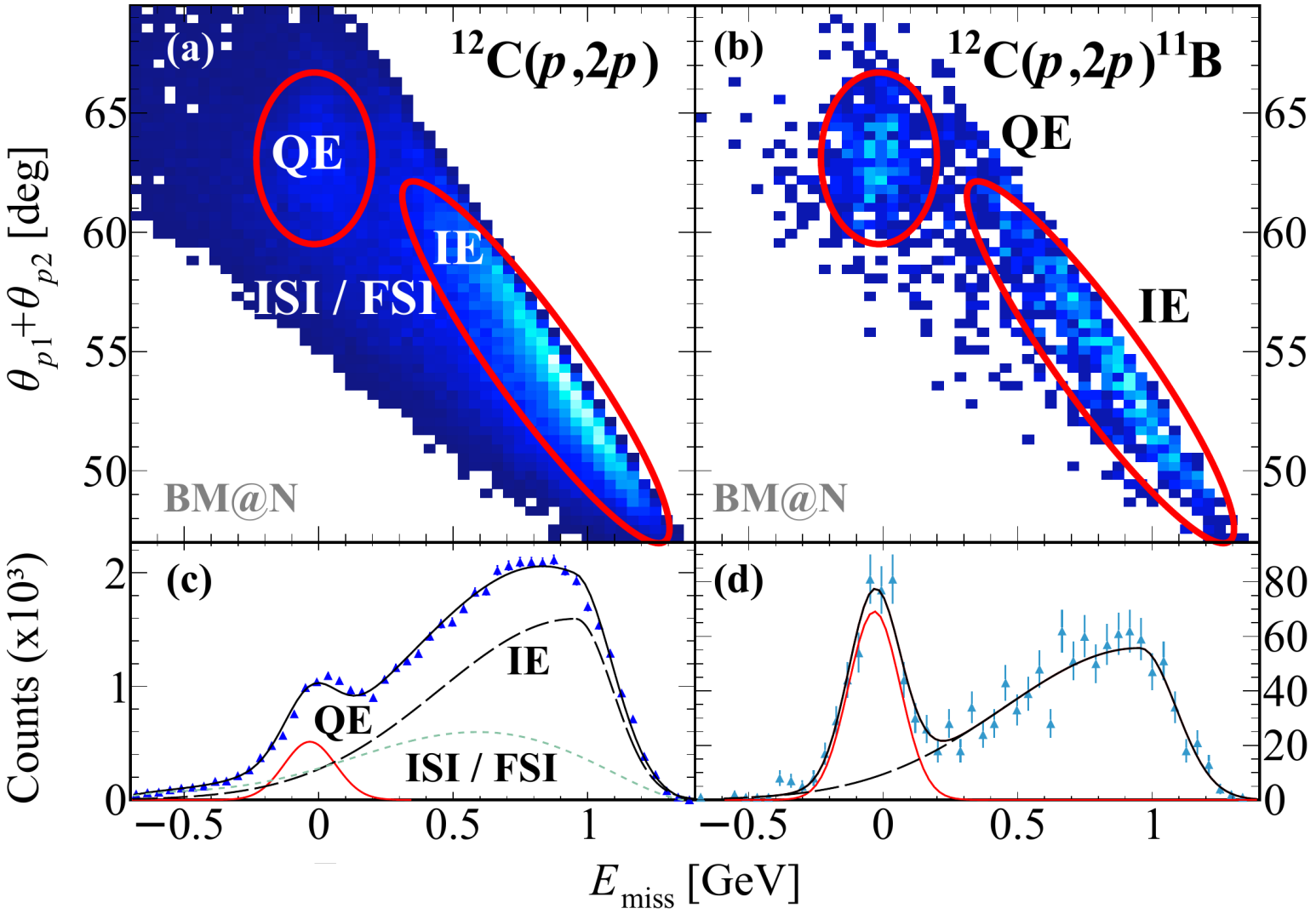

RPC
Si
GEM
TC
Target
Proton
Dipole magnet
Proton

SRC @ BM@N: Fragment



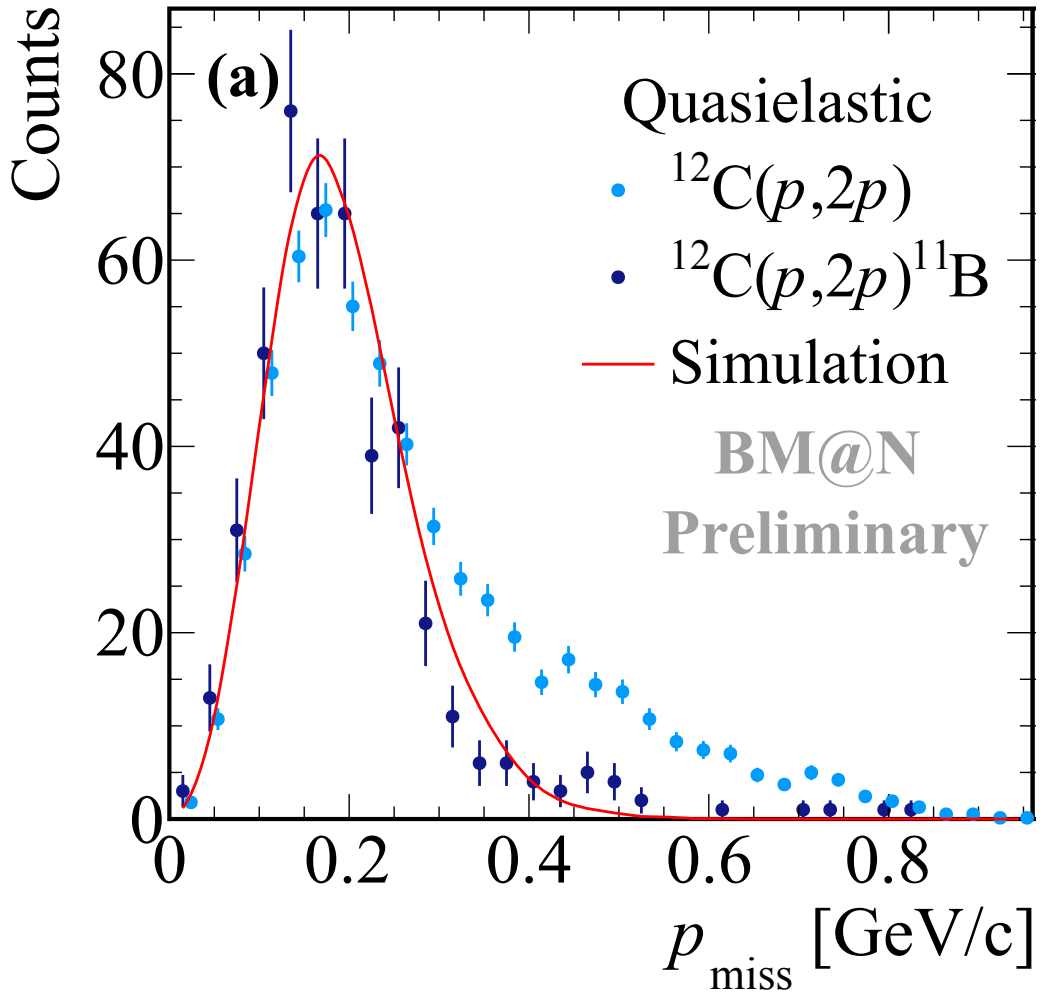


(p,2p)X vs. (p,2p)^{11}B



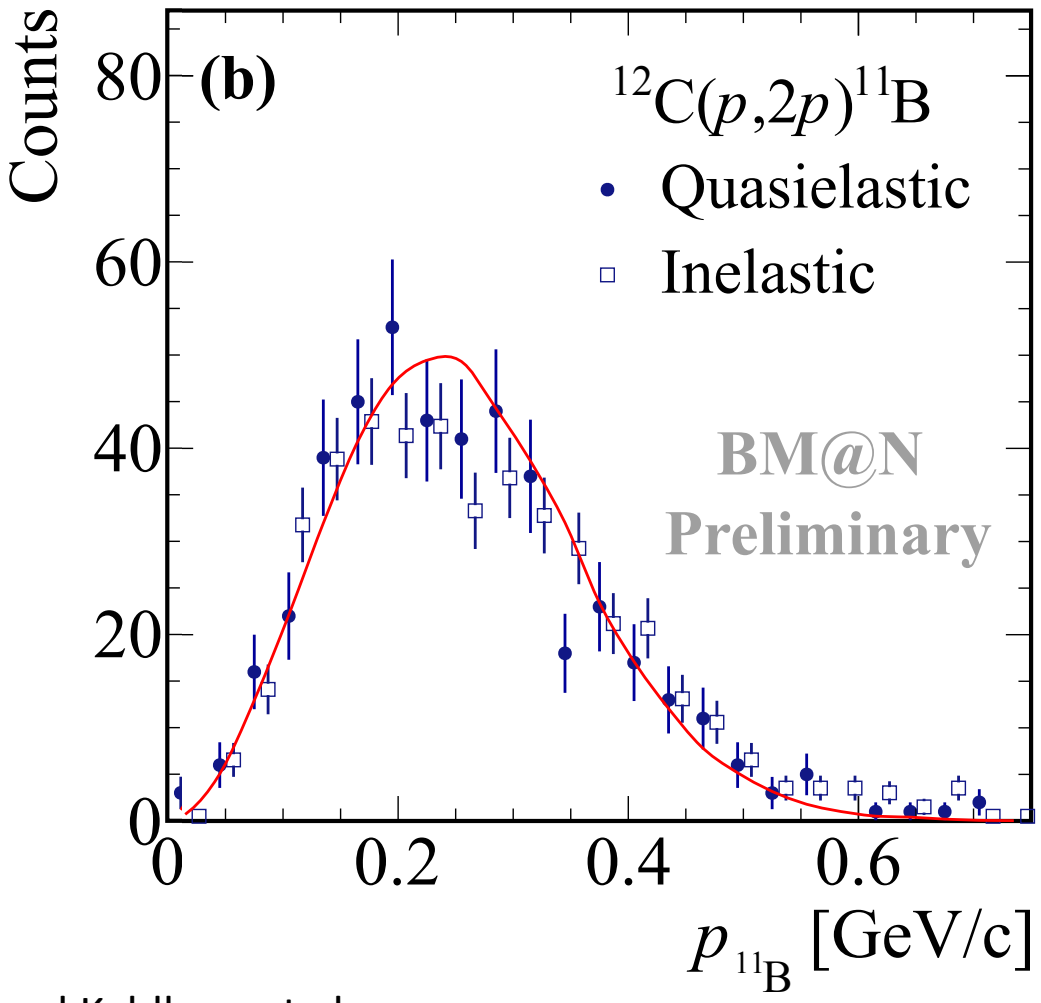
Patsyuk and Kahlbow et al.

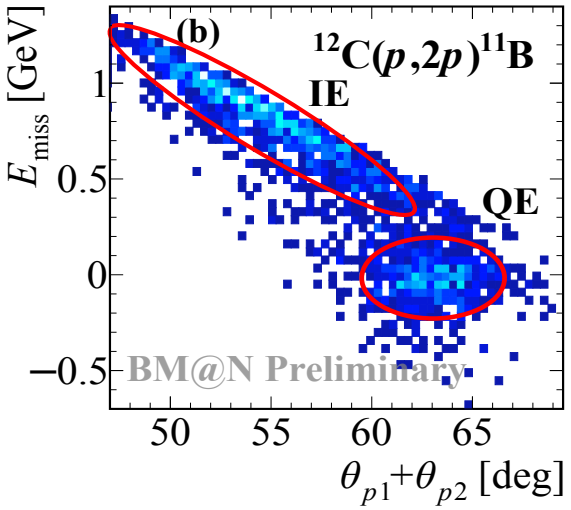
Quasi-elastic: (p,2p)X vs. (p,2p)^{11}B



Patsyuk and Kahlbow et al.

$(p,2p)^{11}B$: Inelastic Vs. Quasielastic





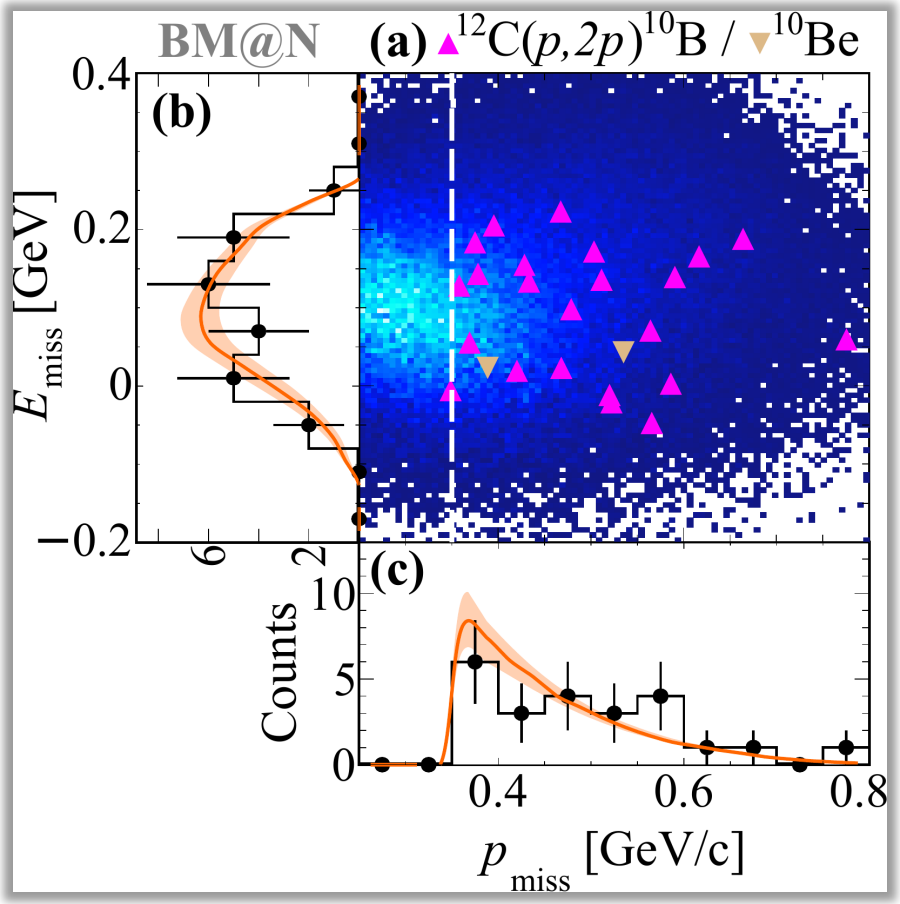
Patsyuk and Kahlbow et al.

First Observation of SRCs

23 ^{10}B events

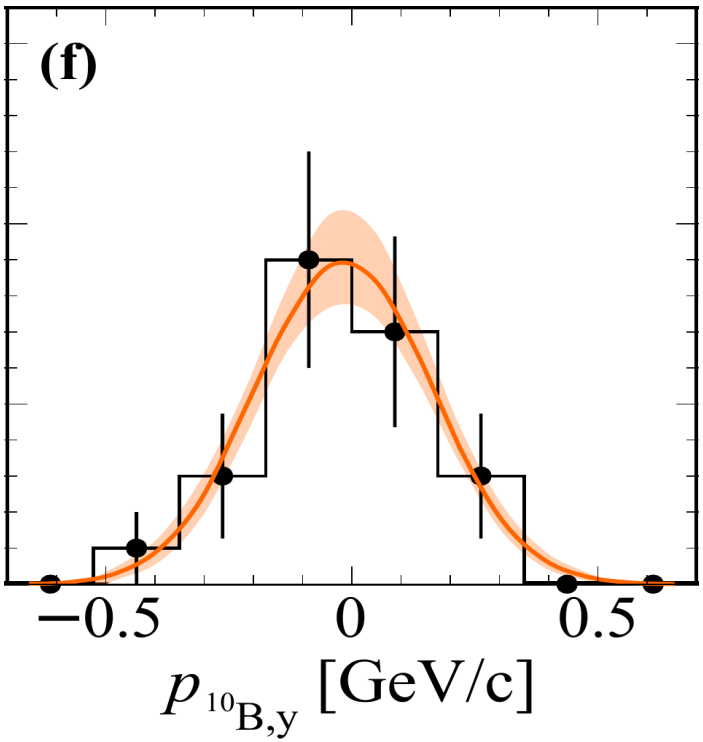
2 ^{10}Be events

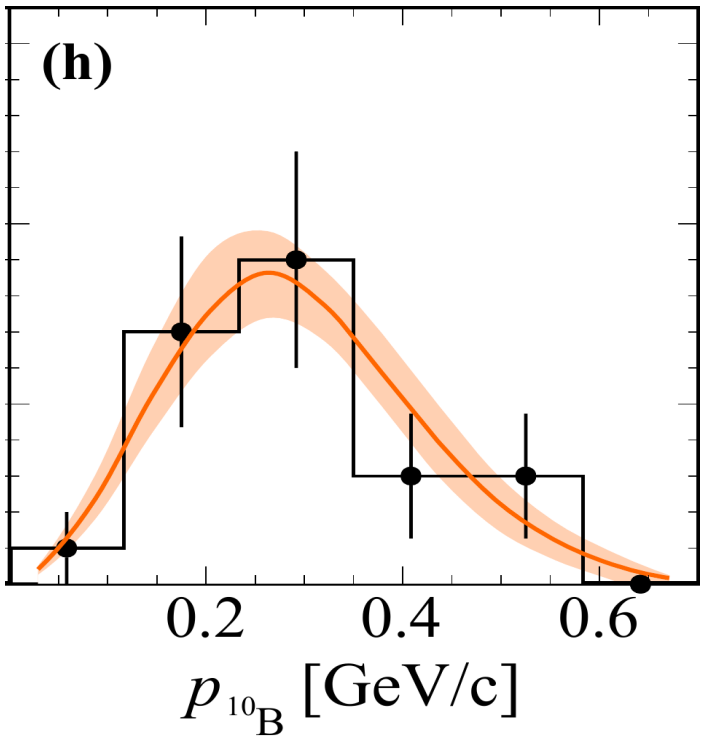
→ *np* pair dominance



Patsyuk and Kahlbow et al.

Fragment Momenta: Pair c.m. Motion





direct extraction: σ = (156 ± 27) MeV/c
=> small c.m. momentum

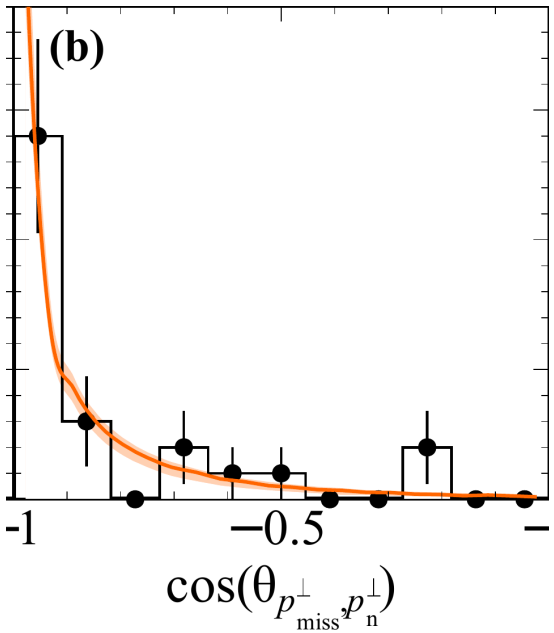
Cohen et al., PRL (2018)

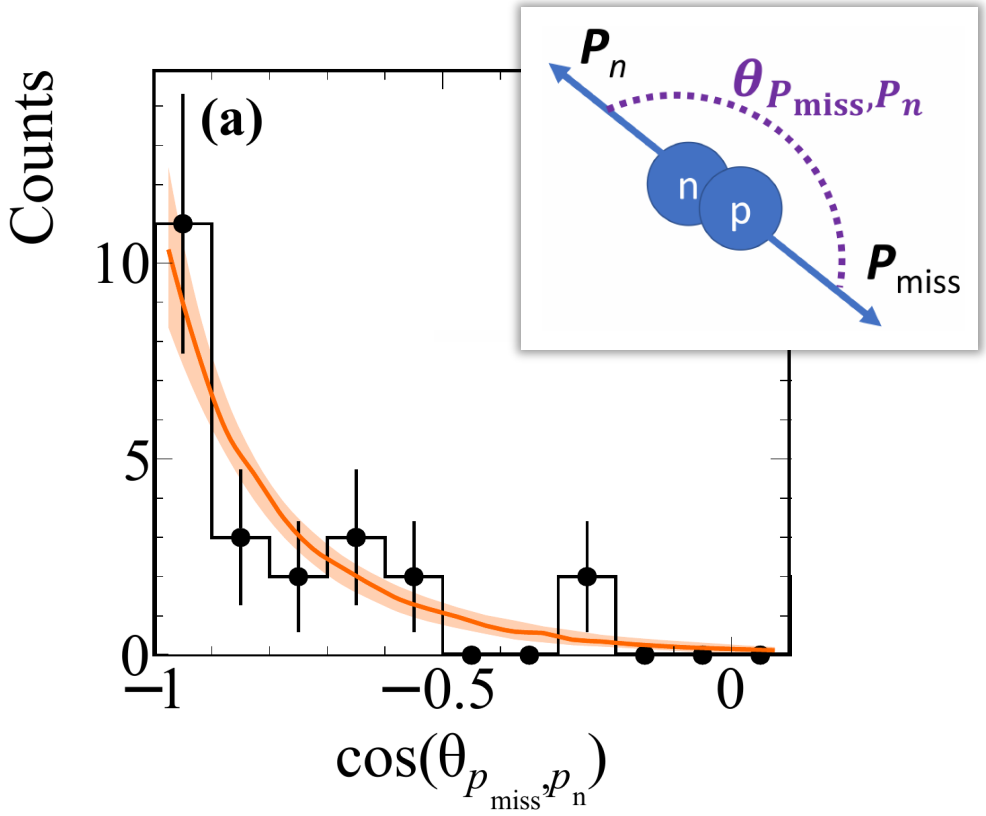
Patsyuk and Kahlbow et al.

SRC Pair: Angular Correlation

strongly correlated pair: nucleon momentum not balanced by A-1

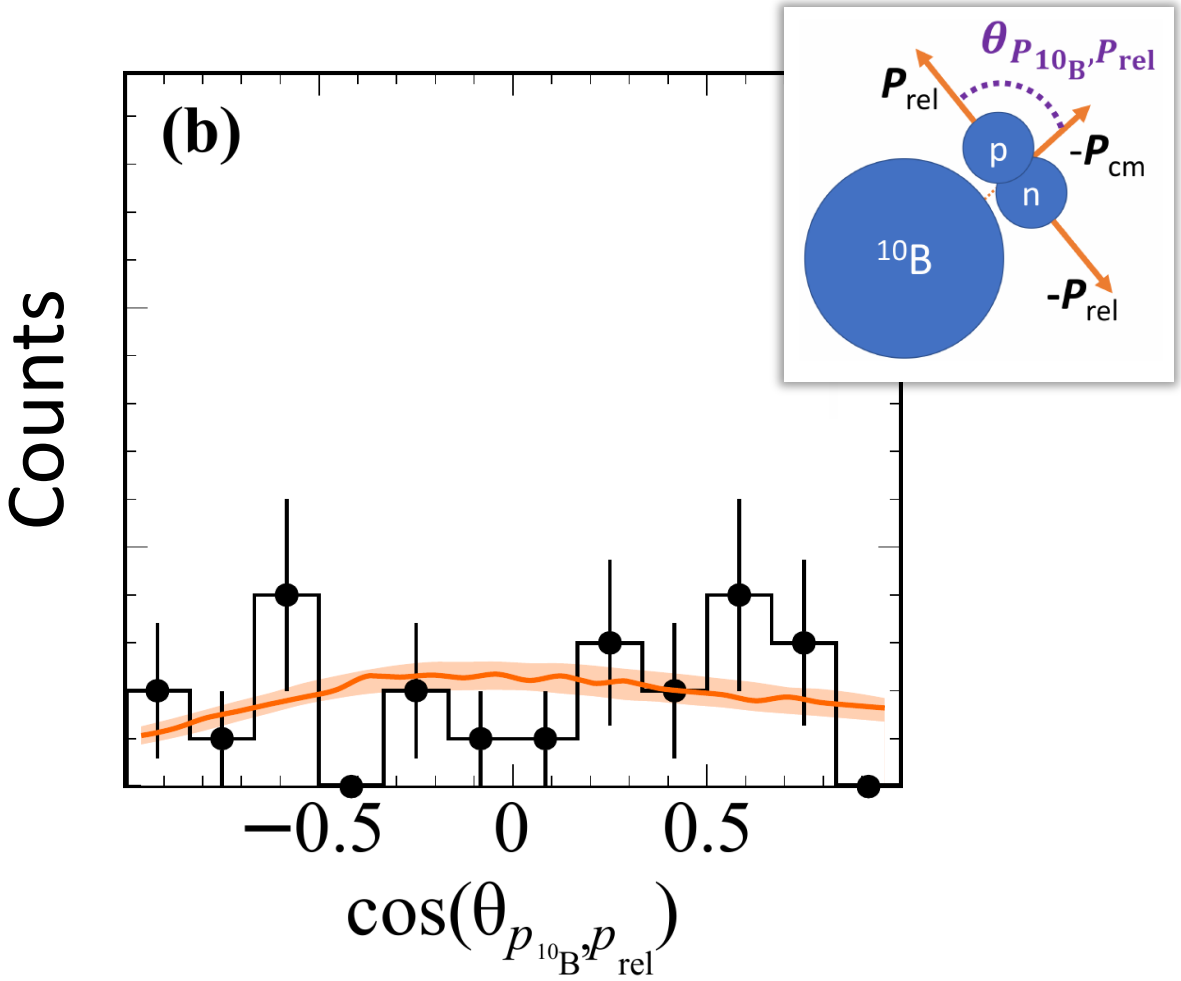
-> NN back-to-back emission





Patsyuk and Kahlbow et al.

Factorization of SRC distribution function



$$f(p_{rel}, p_{c.m.}, \theta_{rel,c.m.}) \approx C(p_{c.m.}) \times \varphi(p_{rel})$$

JINR Results

- First observation of ISI/FSI suppression using fragment detection.

- First observation of SRCs with bound residual A-2 system:

  - Direct measurement of pair c.m. motion
  - **Establishment of factorization!**

1. JLab
   - (e,e’NN): NN interaction
   - (e,e’): Pair abundances

2. JINR
   - (p,2p A-2)n: fully exclusive SRCs

3. Neutron Rich Systems
   - Insight from (e,e’N)
   - Interpretability of (e,e’)

Going neutron rich:

What do excess neutrons do?

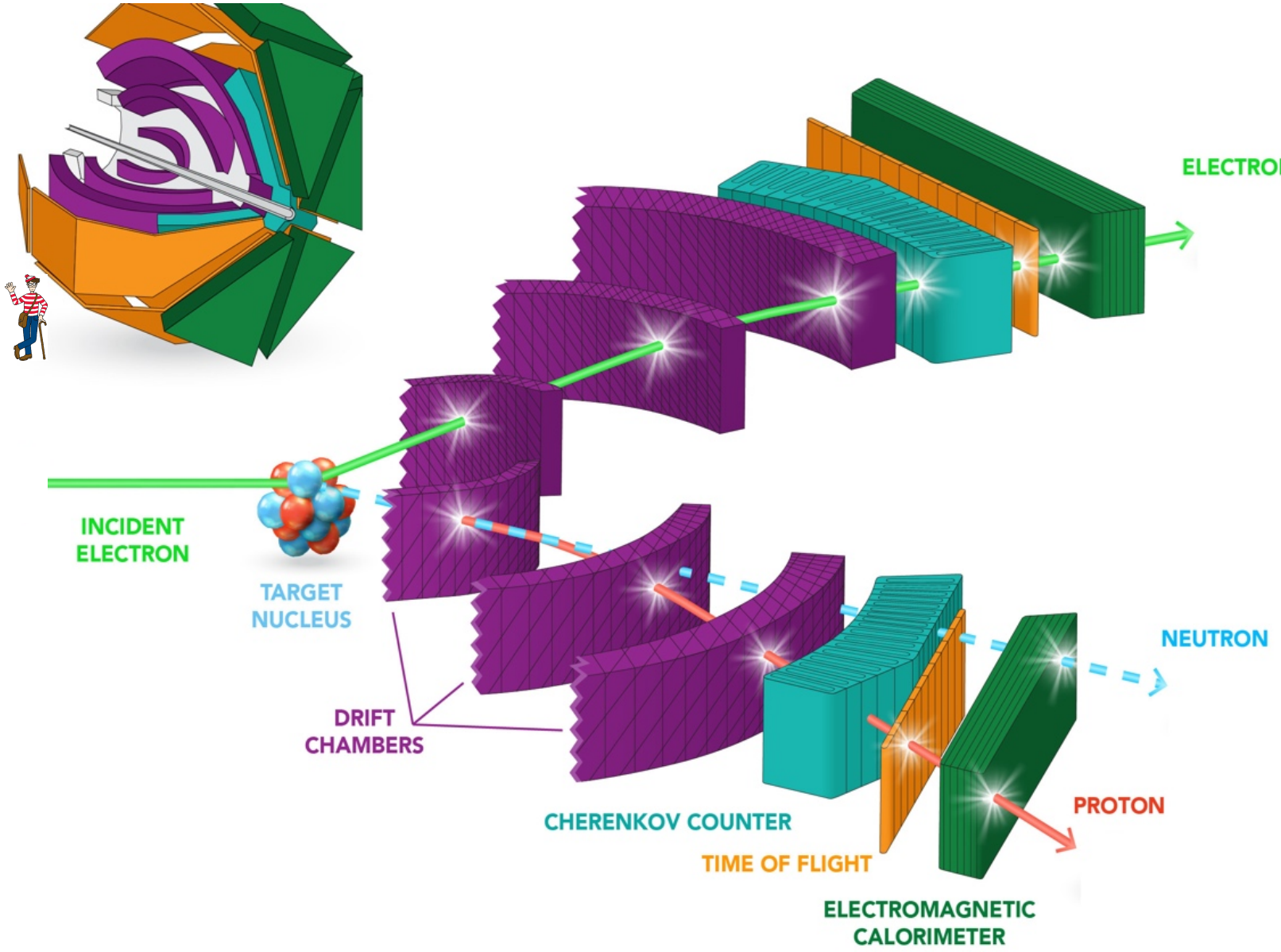
don't correlate?

correlate with each other?

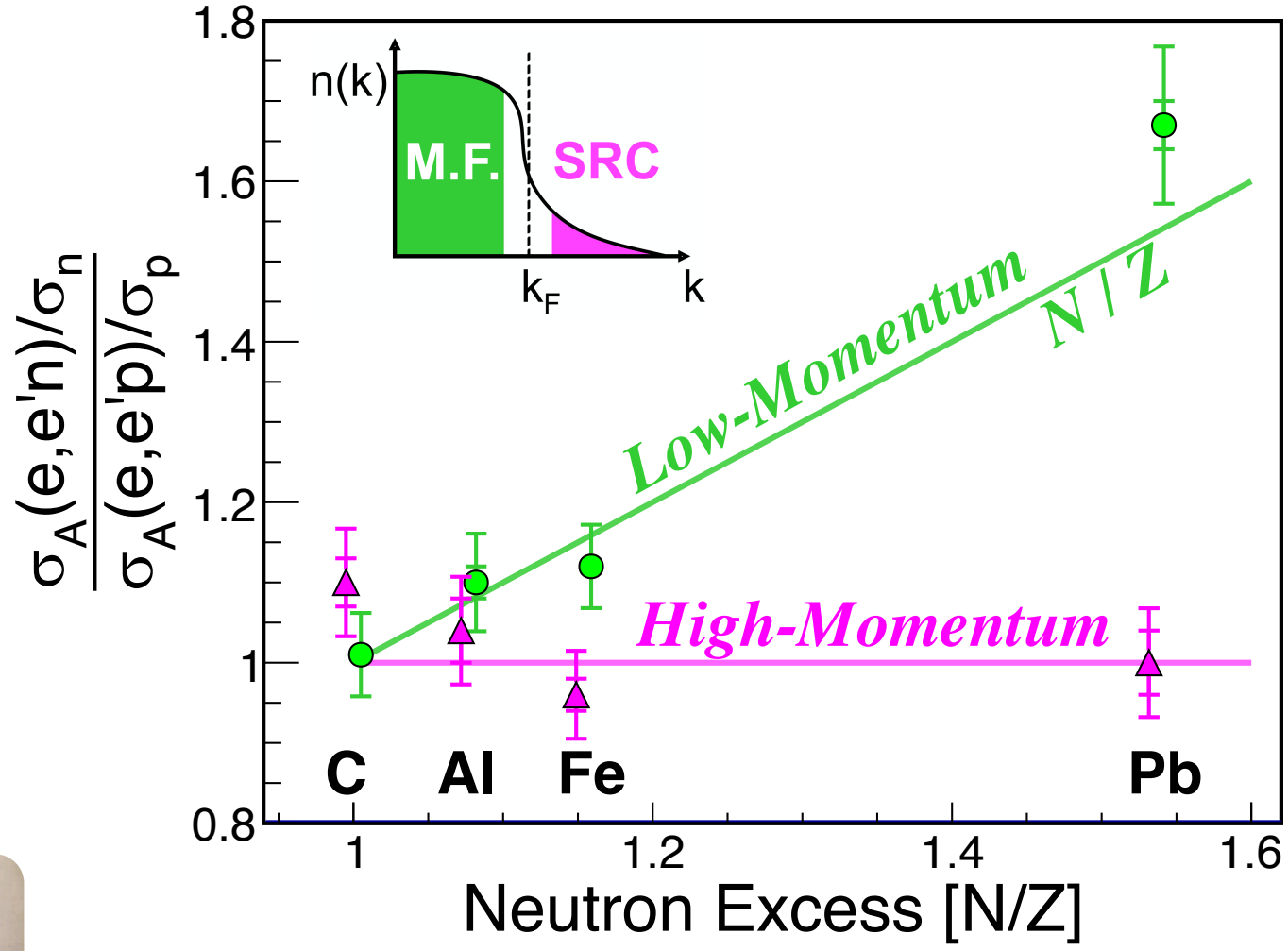
correlate with core protons?

Proton vs. Neutron Knockout

M. Duer



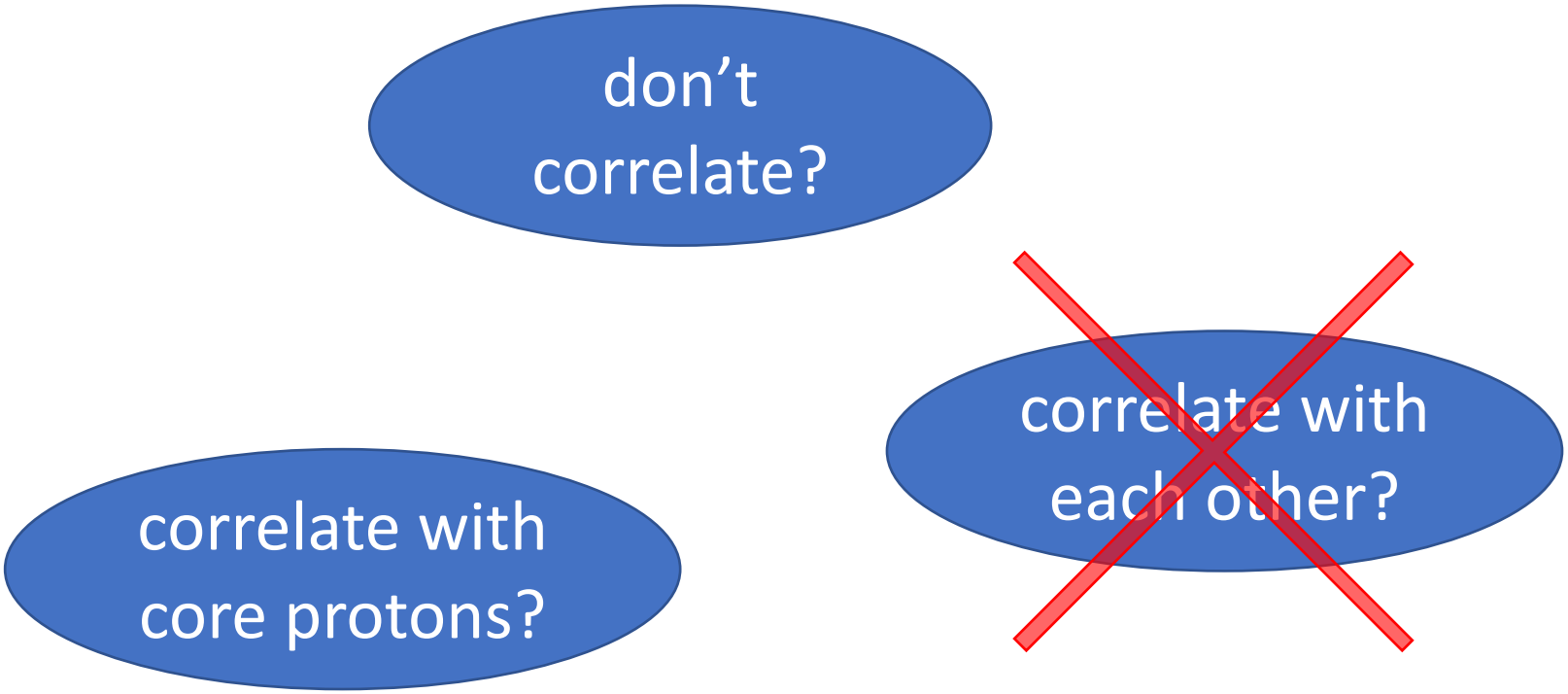
Same # of high-momentum p & n



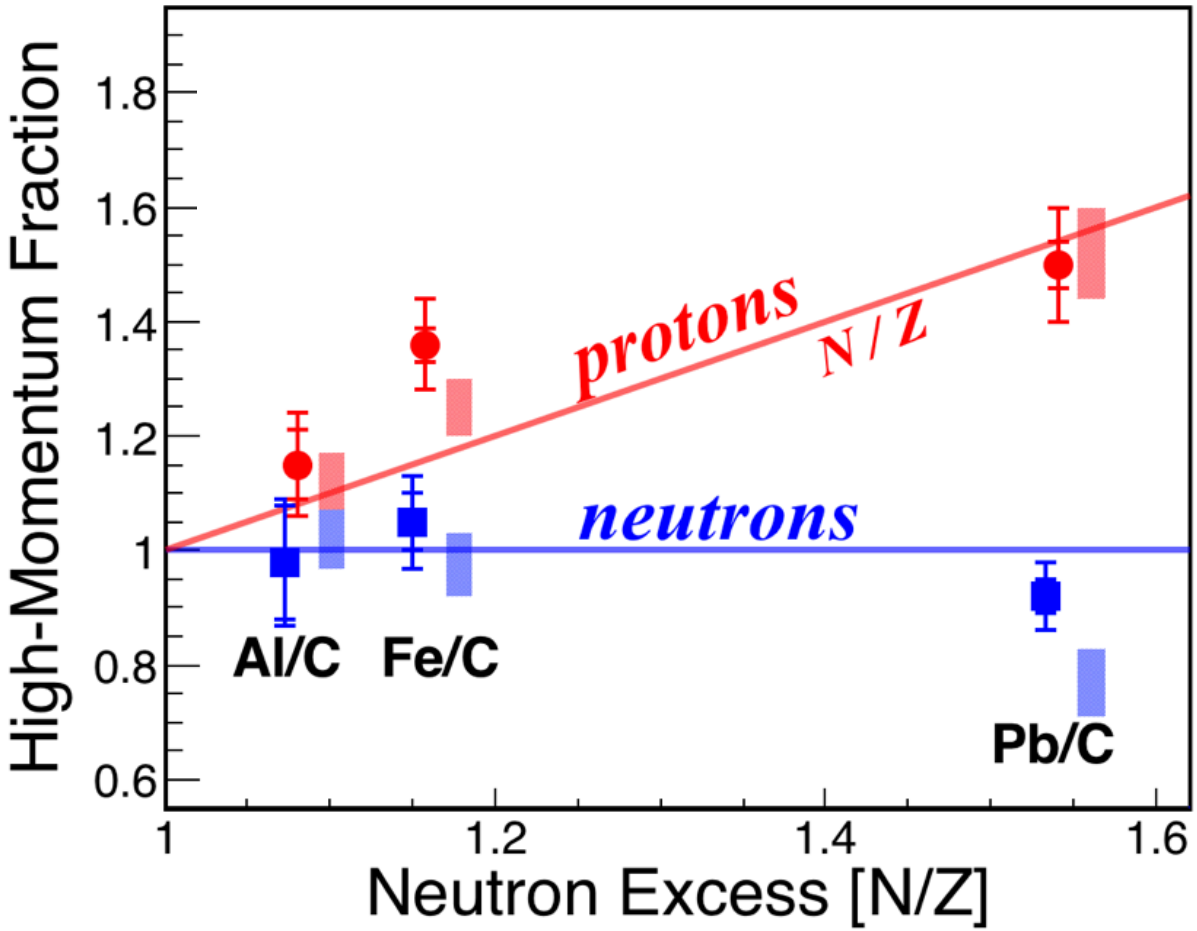
Duer Nature (2018)

Going neutron rich:

What do excess neutrons do?



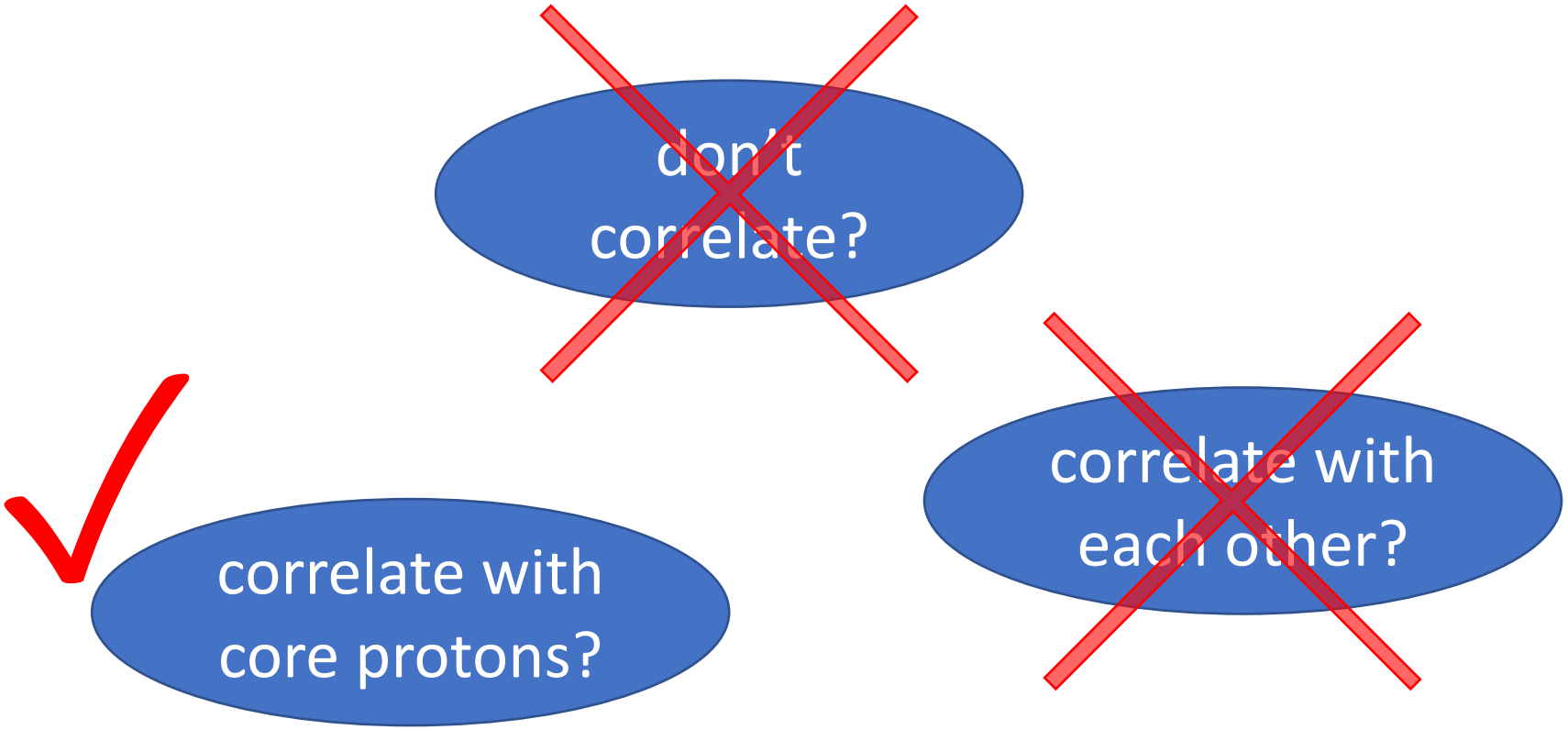
Correlation Probability:
Neutrons saturate Protons grow



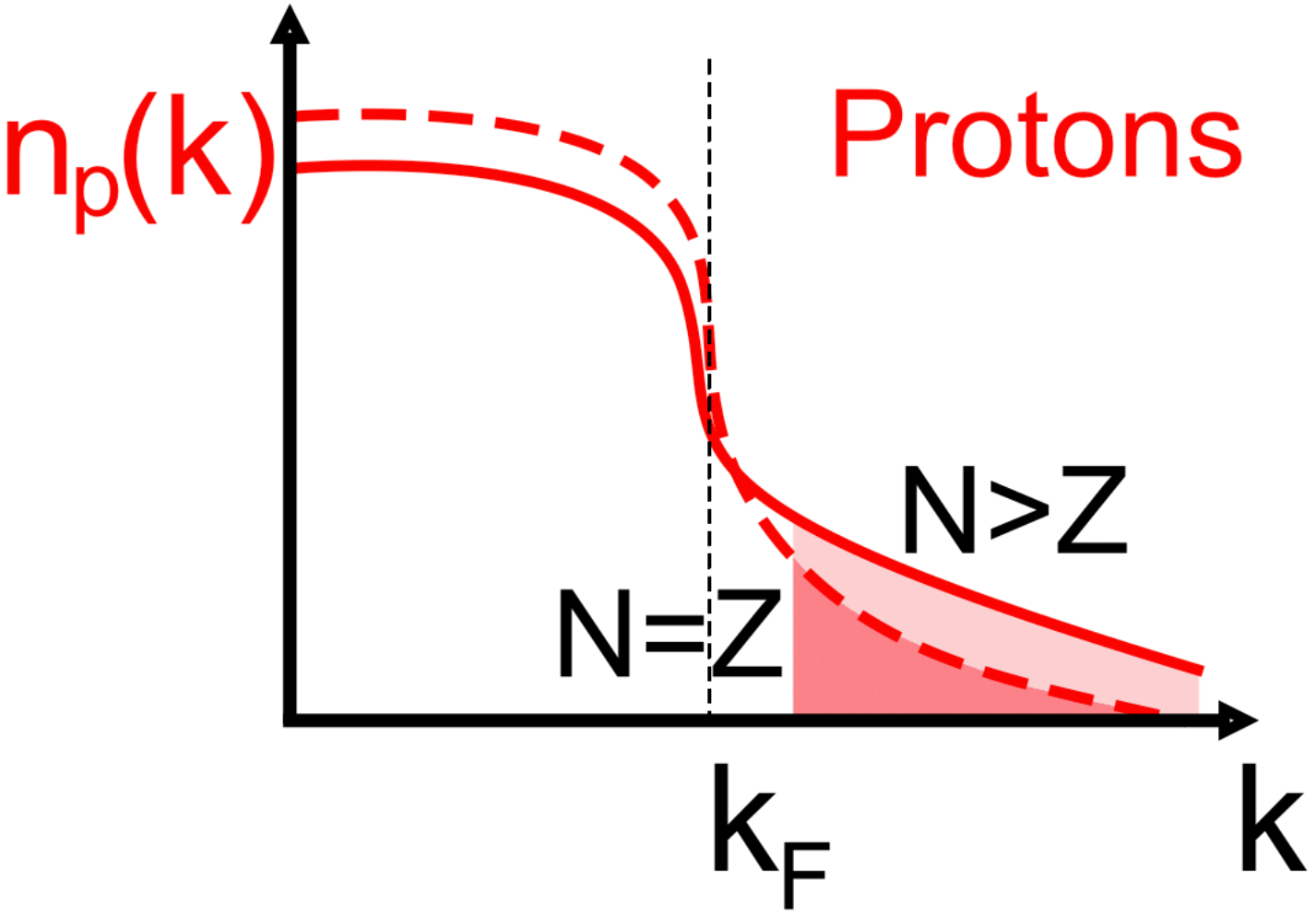
Duer Nature (2018)

Going neutron rich:

What do excess neutrons do?



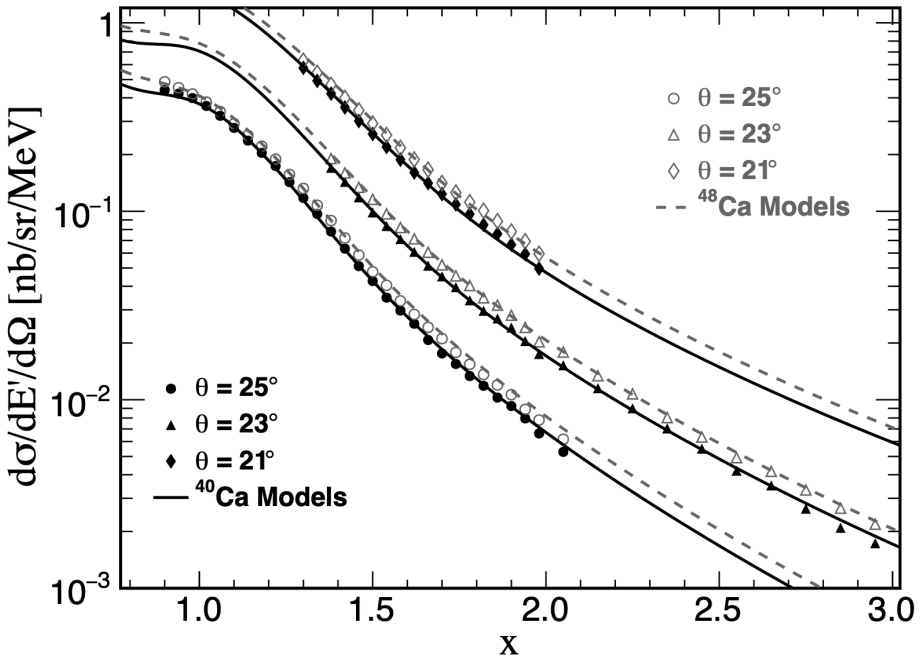
Protons ‘Speed-Up’ In Neutron-Rich Nuclei

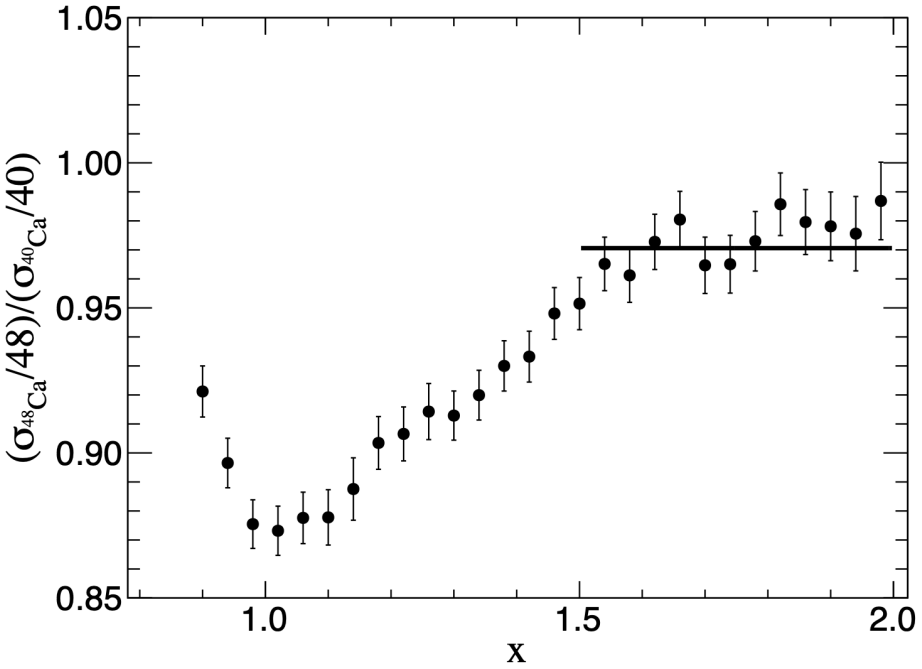


Duer Nature (2018)

Precision ^{40,48}Ca (e,e') measurements

~16% more pairs in ^{48}Ca!





Nguyen et al., arXiv: 2004.11448 (2020)

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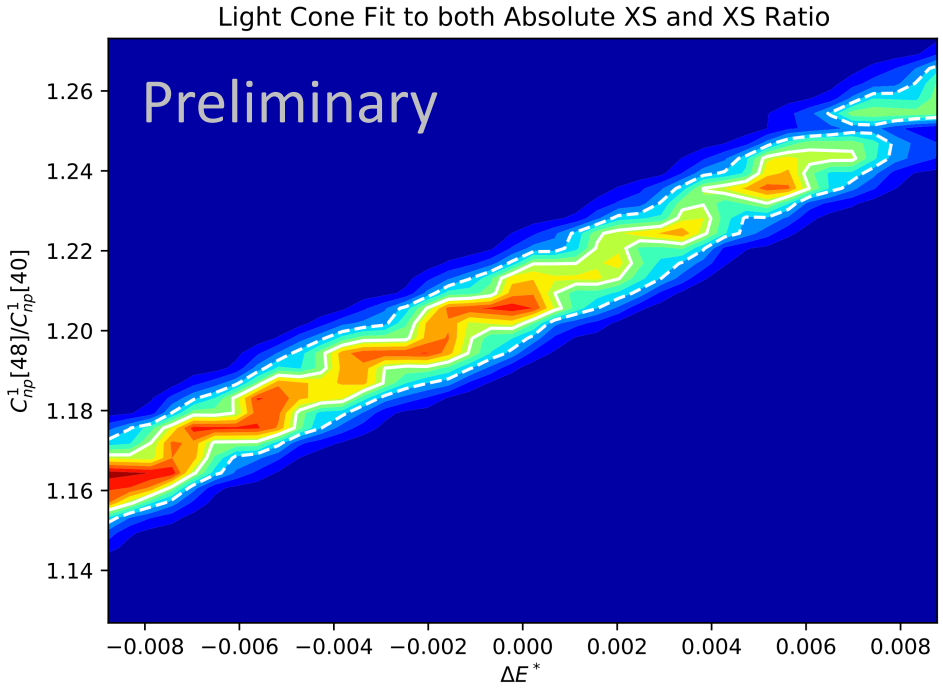
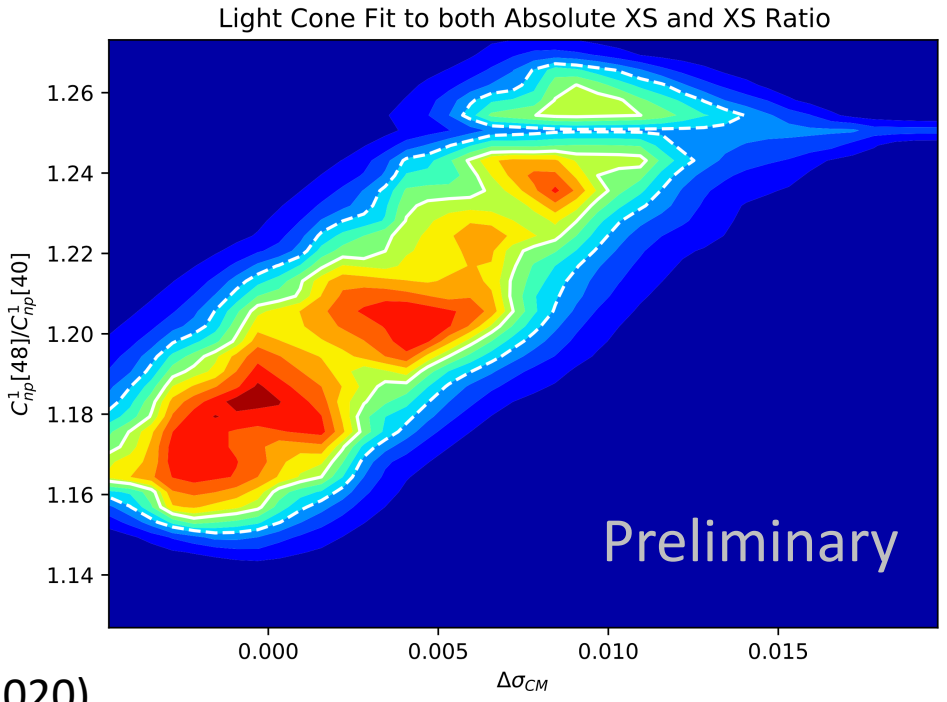
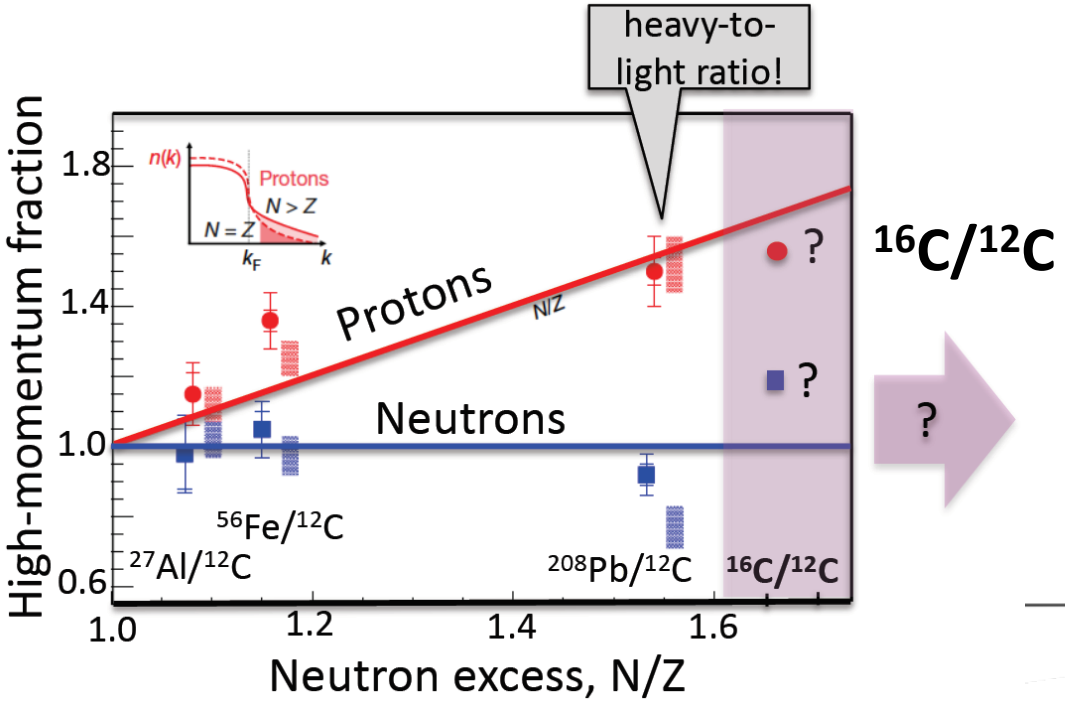




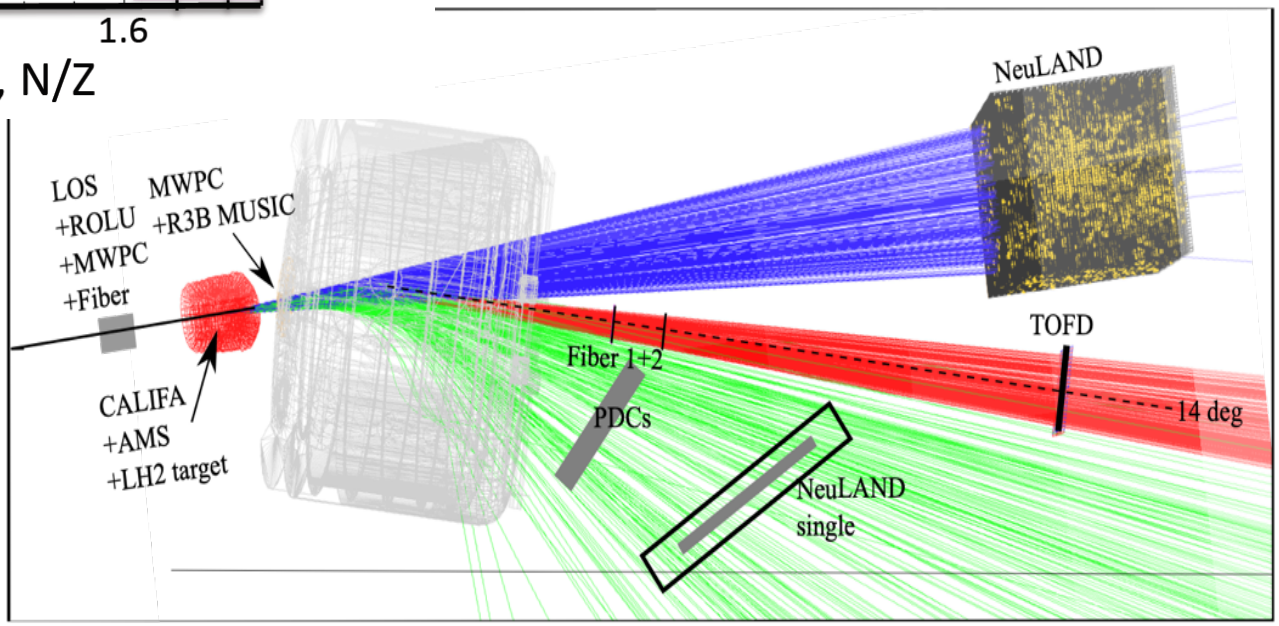
Weiss and Denniston et al., arXiv: 2005.01621 (2020)

Radioactive-ion beams (R^3B@GSI)



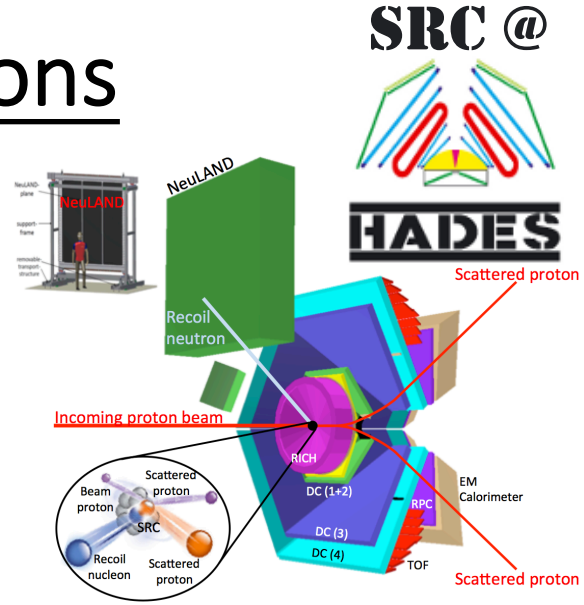
$^{16}C/^{12}C$

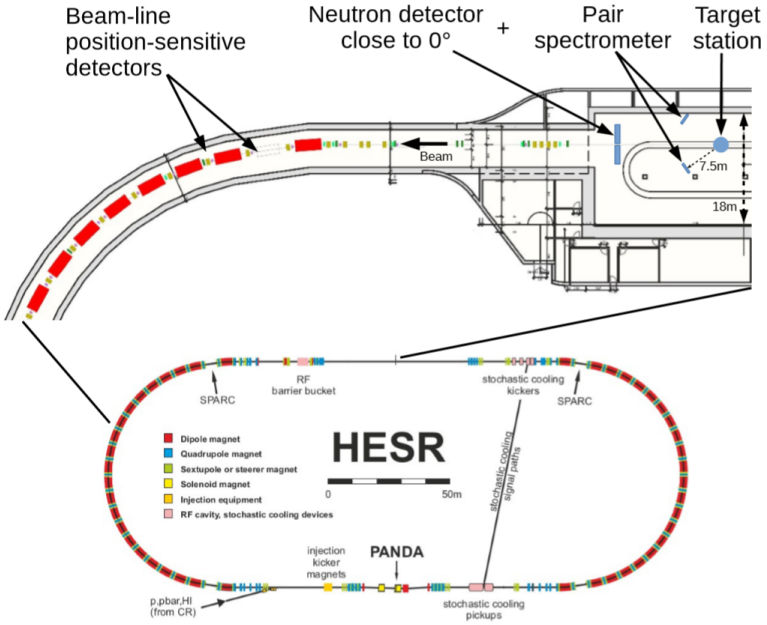
?

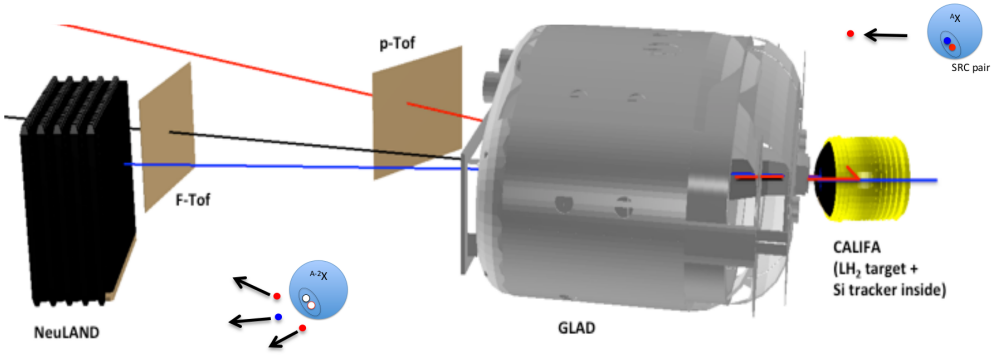


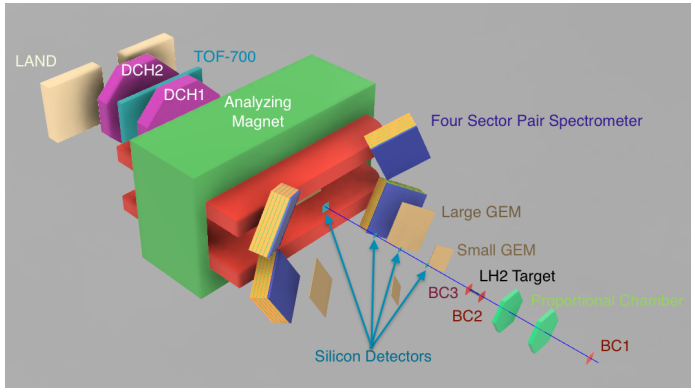
Next Steps in SRC studies \w Hadrons

- **JINR**
- **R3B**
- **HADES**
- **HESR**









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   - (e,e'NN): NN interaction
   - (e,e'): Pair abundances

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   - (p,2p A-2)n: exclusive SRCs

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   - Insight from (e,e'N)
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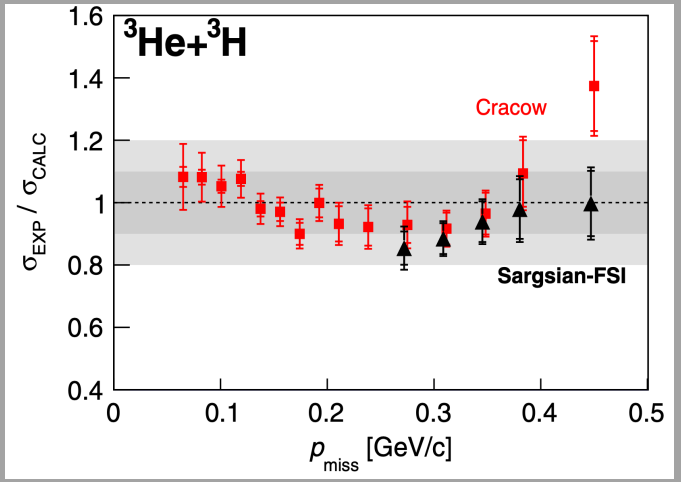

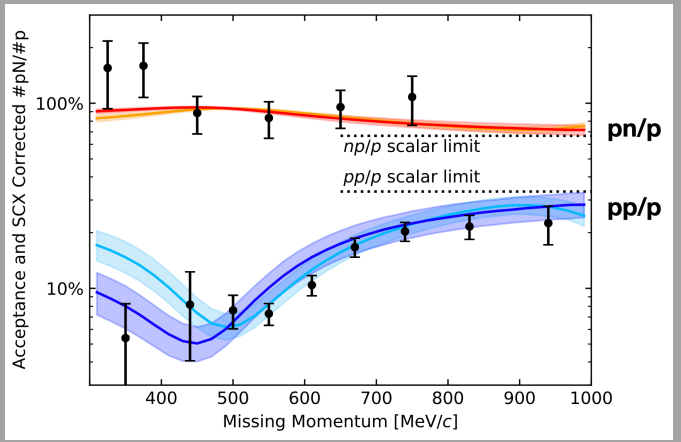

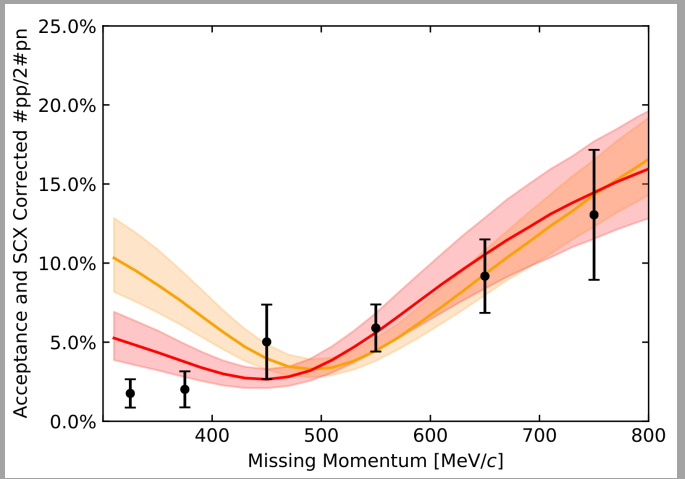

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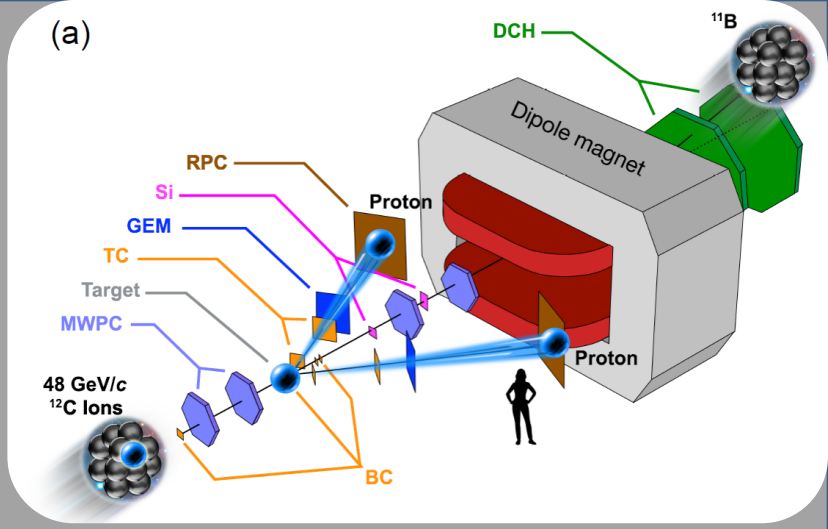

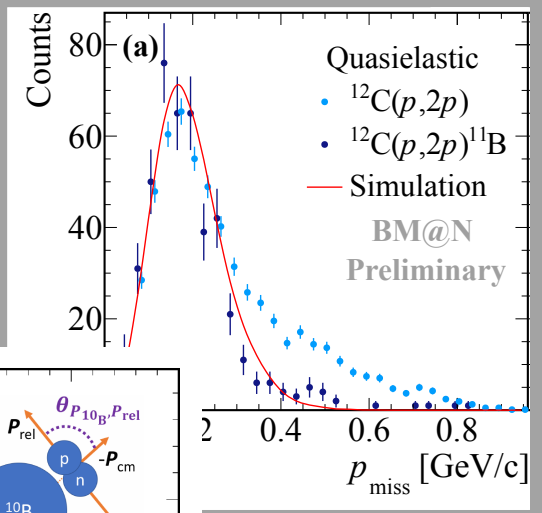

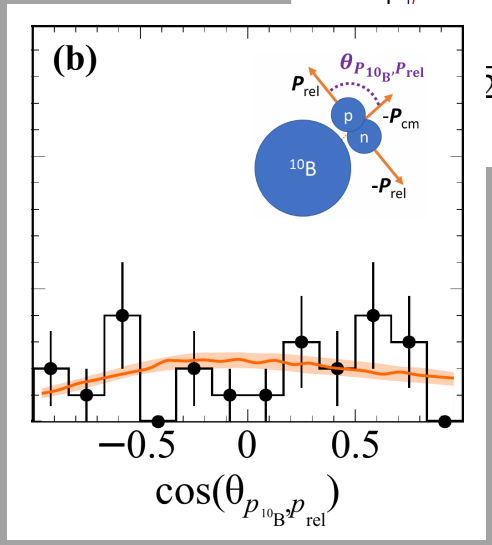

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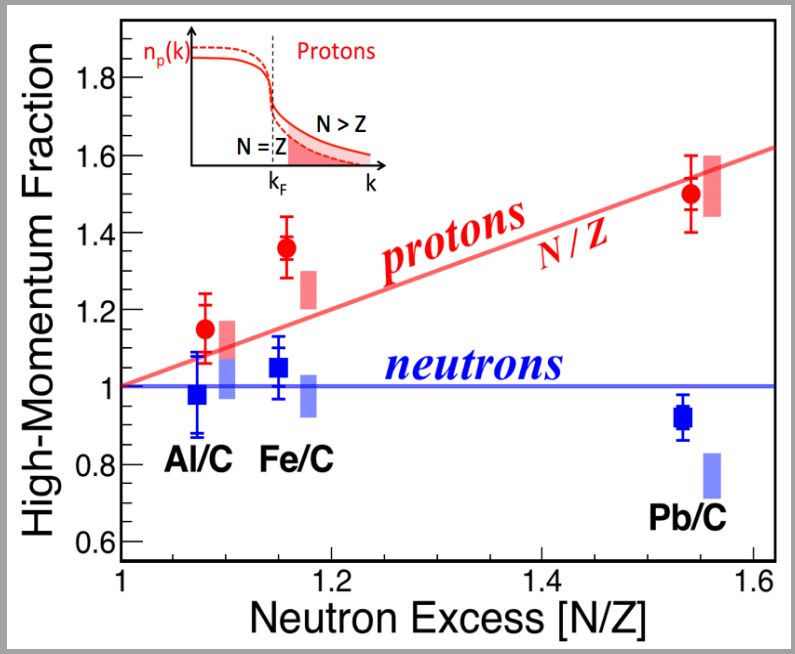

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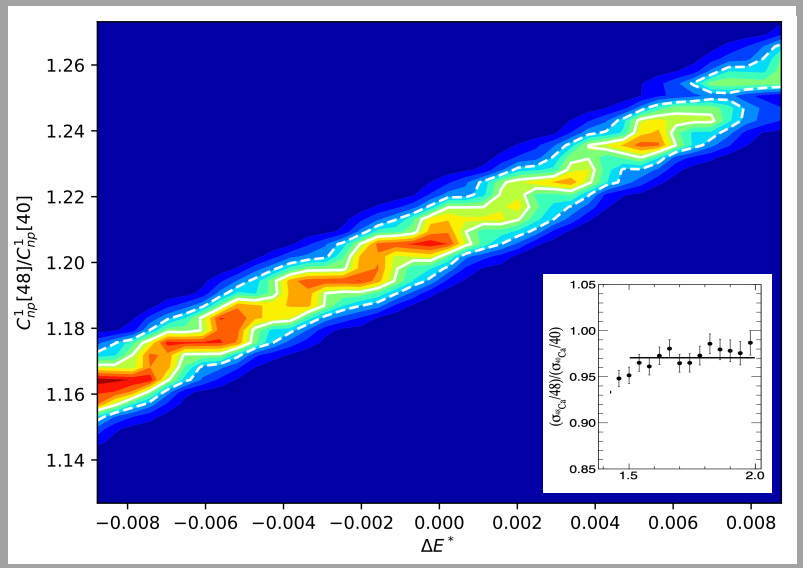
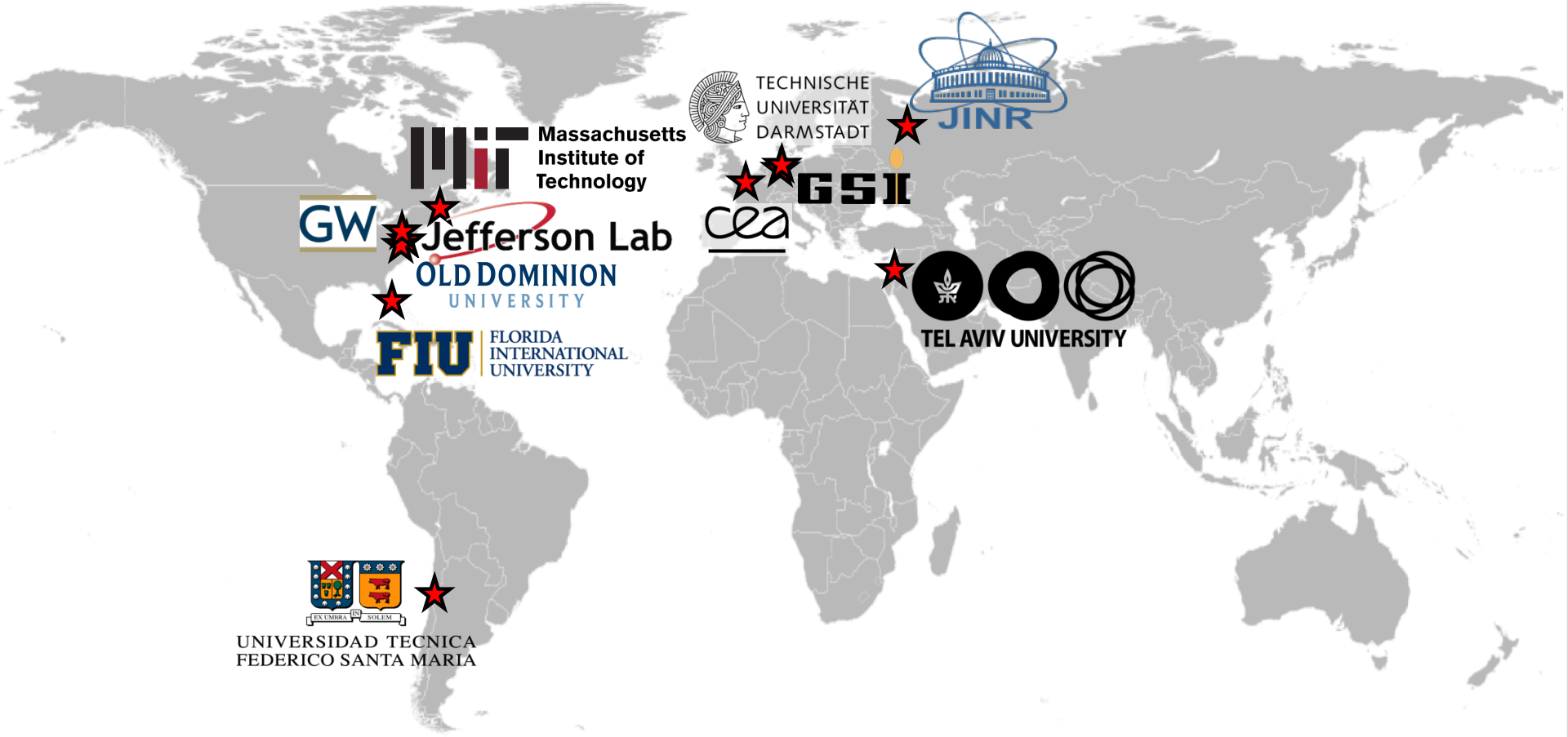
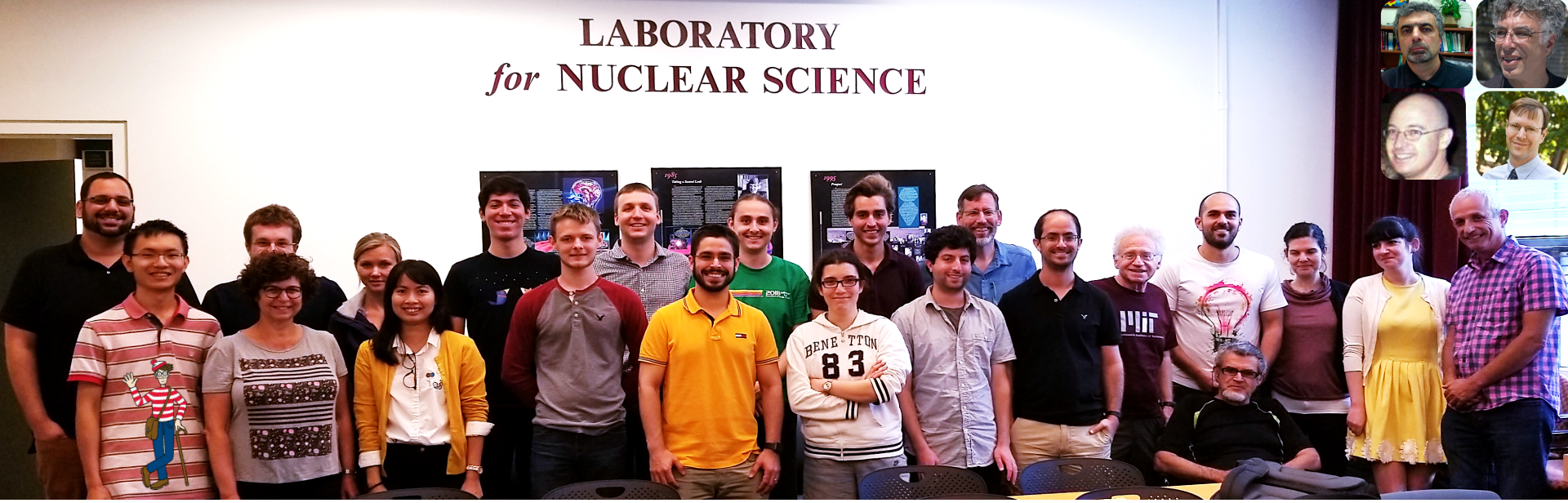


‘Our’ SRC World



+ Many Theory Collaborators: UW, PSU, HUJI, LANL, ANL, Gent, FIU, Perugia, Pisa, …



Afroditi Papadopoulou

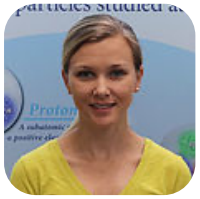
Efrain Segarra

Jackson Pybus

Andrew Denniston

Dr. Adi Ashkenazy

Dr. Dien Nguyen



Dr. Holly Vanse

Dr. Florian Hauenstein

Dr. Julian Kahlbow

Dr. Tyler Kutz

Thank You!